AEDC-TR-75-61

A STUDY OF EXPECTED DATA PRECISION IN THE PROPOSED AEDC HIRT FACILITY

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August 1975

Final Report for Period April 1973 – January 1974

Approved for public release; distribution unlimited.

Prepared for

ARNOLD ENGINEERING DEVELOPMENT CENTER (DY)
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

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This final report was submitted by General Dynamics Corporation, Convair Aerospace Division, San Diego, California 92111, under contract F40600-72-C-0015, with the Arnold Engineering Development Center, Arnold Air Force Station, Tennessee 37389. Mr. Ross G. Roepke was the AEDC project monitor.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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1. REPORT NUMBER AEDC-TR-75-61	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A STUDY OF EXPECTED DATA PRECISION IN THE PROPOSED AEDC HIRT FACILITY		5. TYPE OF REPORT & PERIOD COVERED Final Report - April 1973 thru January 1974 6. PERFORMING ORG. REPORT NUMBER CASD-AFS-73-008
7. AUTHOR(s) J. R. Picklesimer, W. H. Lowe, and D. P. Cumming		8. CONTRACT OR GRANT NUMBER(s) F40600-73-C-0015
9. PERFORMING ORGANIZATION NAME AND ADDRESS General Dynamics Corporation Convair Aerospace Division San Diego, California 92111		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 65802F
11. CONTROLLING OFFICE NAME AND ADDRESS Arnold Engineering Development Center(DYFS) Air Force Systems Command Arnold Air Force Station, TN 37389		12. REPORT DATE August 1975 13. NUMBER OF PAGES 63
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in DDC

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

wind tunnels
Reynolds number
data acquisition
precision
accuracy

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

AEDC has proposed an 8 x 10 foot Transonic Wind Tunnel (HIRT) operating on a Ludwieg tube concept. This facility is designed to meet the need to properly simulate the full-scale Reynolds numbers of current and future aircraft. HIRT differs from conventional wind tunnels in the characteristics of short run duration, high operating pressures, low temperatures and high aerodynamic loads. The purpose of this study was to assess the precision of the test

20. ABSTRACT (Continued)

data expected from HIRT and to examine HIRT to determine if its mode of operation would adversely affect data precision. It was assumed that the precision of the drag measurement could be used as the yardstick for evaluating over-all precision of facility test data. To establish a baseline from which the predicted precision of model data gleaned in HIRT could be compared, a transonic tunnel data accuracy questionnaire was completed by five leading domestic transonic facilities. The responses to this questionnaire are summarized in this report. These facilities estimated that drag was measured within ±0.0005 C_D. The short run duration available in HIRT requires that close attention must be paid to system dynamics including the dynamic behavior of the model-balance-sting assembly and the model pressure measuring system. This study concludes that by using the proper application of electrical filtering, limiting model pitch acceleration, and using a suggested composite sting design, the adverse effects of model-balance-sting dynamics on data precision can be reduced to within acceptable limits. Also, base or cavity pressures can be accurately measured at the rapid pitch rates required for HIRT. However, this study showed that the error in drag coefficient due to balance error could be as large as ±0.0009 C_D.

AFSC
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PREFACE

This report describes the work performed on Air Force Contract F40600-72-C-0015 (Phase II) by General Dynamics/Convair Aerospace Division, San Diego operation, San Diego, California. The contractor's number, CASD-AFS-73-007, is used to identify the report.

This study is one of a four-part program conducted for Phase II. The other three studies are:

a. AEDC-TR-75-60, "Study of Multipiece Flow-Through Wind Tunnel Models for HIRT."

b. AEDC-TR-75-62, "Study of HIRT Model Aeroelastic Characteristics in Reference to the Aeroelastic Nature of the Flight Vehicle."

c. AEDC-TR-75-63, "Study of Six-Component Internal Strain Gage Balances for Use in the HIRT Facility."

This work was administered by the Department of the Air Force, Headquarters, Arnold Engineering Development Center (TMP), Arnold Air Force Station, Tennessee. Mr. Ross G. Roepke, AEDC (DYX), is the Air Force technical representative.

This program was conducted in the Research and Engineering Department of General Dynamics/Convair Aerospace Division and was managed by S. A. Griffin. The work for this study was accomplished between April 1973 and January 1974.

The authors, J. R. Picklesimer, W. H. Lowe, and D. P. Cumming, wish to acknowledge the contribution of Messrs. H. Riead, C. E. Jackson, S. P. Tyler, C. E. Kuchar, and M. L. Kuszewski in the preparation of this report.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

1.1 BACKGROUND

There has been a growing demand in recent years for aerodynamic test facilities that operate at the flight Reynolds numbers of current and future aircraft. Such facilities are needed for accurate prediction of aircraft performance. A number of aerodynamic phenomena are sensitive to Reynolds number, including shock-boundary layer interaction, flow separation, and buffet. Examination of the simulation capability available in existing facilities reveals that only one-tenth the required Reynolds number is currently available (Reference 1). Clearly, new facilities are required. The Arnold Engineering Development Center (AEDC) has proposed an 8- × 10-foot transonic tunnel operating on a Ludwieg tube concept to fill this need.* The proposed facility, known as HIRT, will have a capability of $R_e = 2 \times 10^8$ per foot. HIRT will not only function as the primary test facility in this country for high Reynolds number simulation, but will also be available as a validation tool for data obtained in low and medium Reynolds number facilities.

The primary justification for HIRT and other similar facilities is to provide accurate data for aircraft performance estimation by improving the simulation process. The extrapolation of data obtained in small or low Reynolds number tunnels to flight conditions becomes risky when viscous phenomena can produce gross changes in flow patterns on the aircraft, which is the case in the transonic speed range. However, the operation of a facility at very high Reynolds number may involve such compromises in testing technology that the advantages gained by simulating flight Reynolds number are effectively cancelled by the problems in acquiring accurate data.

It is therefore appropriate that the precision of data to be expected from the proposed facility be carefully examined to determine if it is adequate to provide the required aircraft performance data. This is the purpose of this study. In it we have examined the requirements for data precision to predict actual aircraft performance, we have evaluated the capability of existing facilities to meet these requirements, and we have examined HIRT in detail to determine if its mode of operation will pose serious problems with respect to data accuracy. However, before such a study begins, it is necessary to understand how HIRT operates and how this operation differs from conventional facilities.

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*Since completion of this report by Convair, a final decision was made not to construct the HIRT at AEDC in favor of a continuous cryogenic wind tunnel, site as yet undetermined.

1. Ross G. Roepke, "The High Reynolds Number Transonic Wind Tunnel HIRT Proposed as Part of the National Aeronautical Facilities Program," AIAA Paper 72-1035, 13 September 1972.

1.2 DESCRIPTION OF HIRT

The HIRT facility, shown in Figure 1, is described in detail in Reference 1. It is a Ludwieg tube tunnel consisting of a charge tube 15 feet in diameter and 1660 feet long, a nozzle, an 8- × 10-foot test section, discharge diffuser, and start valve array. Before a run, the complete circuit is charged to a pressure of up to 700 psia. When the quick action start valves downstream of the test section are opened, a centered expansion wave moves down the charge tube, reflects at its end, and returns. A steady, uniform flow exists in the test section. The arrival of the reflected expansion wave at the test section ends the run. For HIRT the run time is about 2.5 seconds.

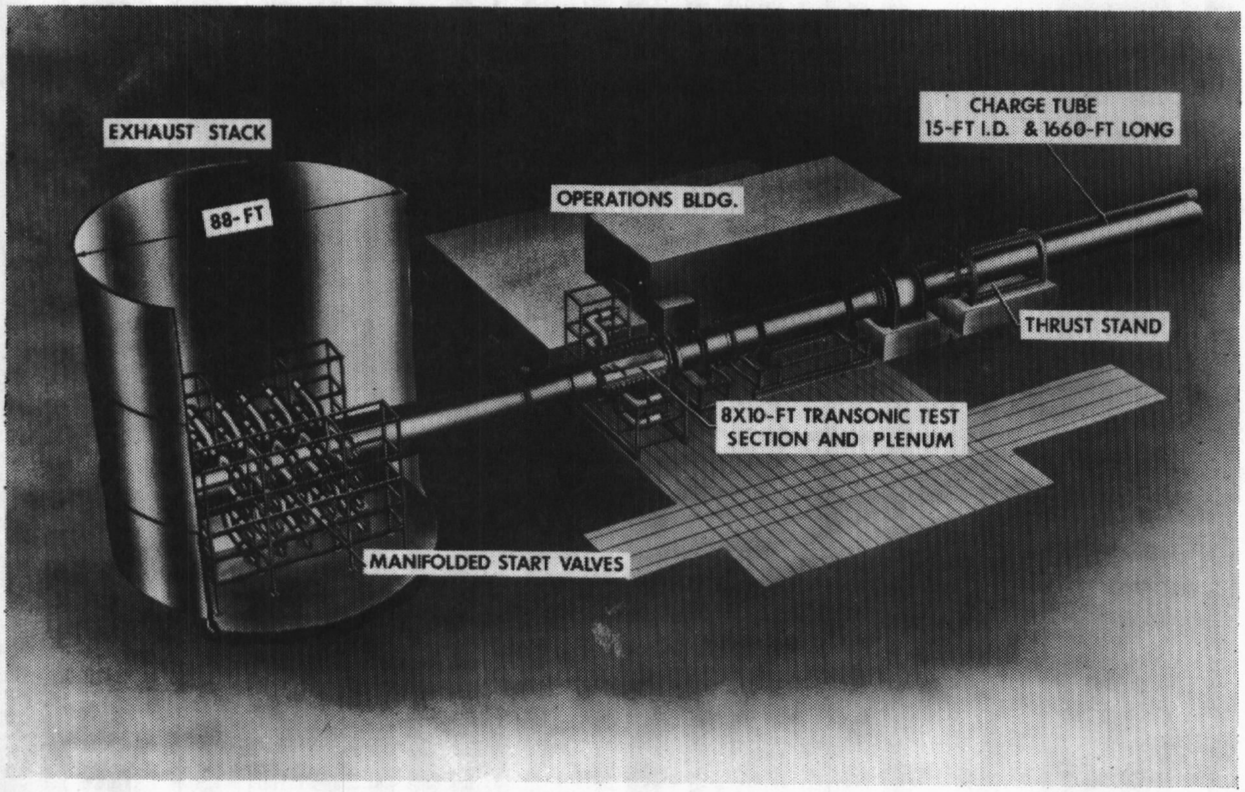


Figure 1. Artist's Concept of High Reynolds Number Wind Tunnel (HIRT)

The flow process results in an abrupt change of conditions at the model. For example, at Mach 1.0 and initial charge conditions of 700 psia and 430°R, the stagnation conditions drop to 496 psia and 390°R. Test section conditions drop to 262 psia and 325°R. The dynamic pressure under these conditions is 26,412 psf.

Thus, the HIRT facility differs from conventional wind tunnels in the characteristics of short run duration, high operating pressures, low temperatures, and high aerodynamic loads.

1.3 GENERAL REQUIREMENTS FOR WIND TUNNEL DATA ACCURACY

Before the accuracy of existing or proposed facilities is examined, it is helpful to understand the end use of wind tunnel data in the aircraft development process and the impact that data accuracy has on that process. Wind tunnel testing is a critical step in aircraft development. It allows the design team to evaluate the predicted performance; to optimize the design; to determine loads data; and to identify, evaluate, and correct operational problems with the aircraft. The wind tunnel also allows the aircraft customer to evaluate competing designs with respect to performance. The data from the wind tunnel is corrected for scale effects and used to predict actual flight performance. Since errors in performance prediction can be very significant in both an economic and operational sense to the developer and customer, it is important to provide accurate wind tunnel data.

In general, the most critical parameter in aircraft performance is aircraft drag. Errors in other components, such as lift and pitching moment, affect mission performance insofar as they affect the drag at the trimmed flight condition. This is illustrated in Figure 2. The aircraft designer must know the true aircraft trim curve. Data from the wind tunnel is adjusted to flight conditions. Errors in either the original data or the adjustment are reflected in a shift in the trim curve. Since lift is fixed by aircraft weight or maneuver loading at the particular flight condition, the impact of data error is an error in drag at that condition. Similarly, errors in

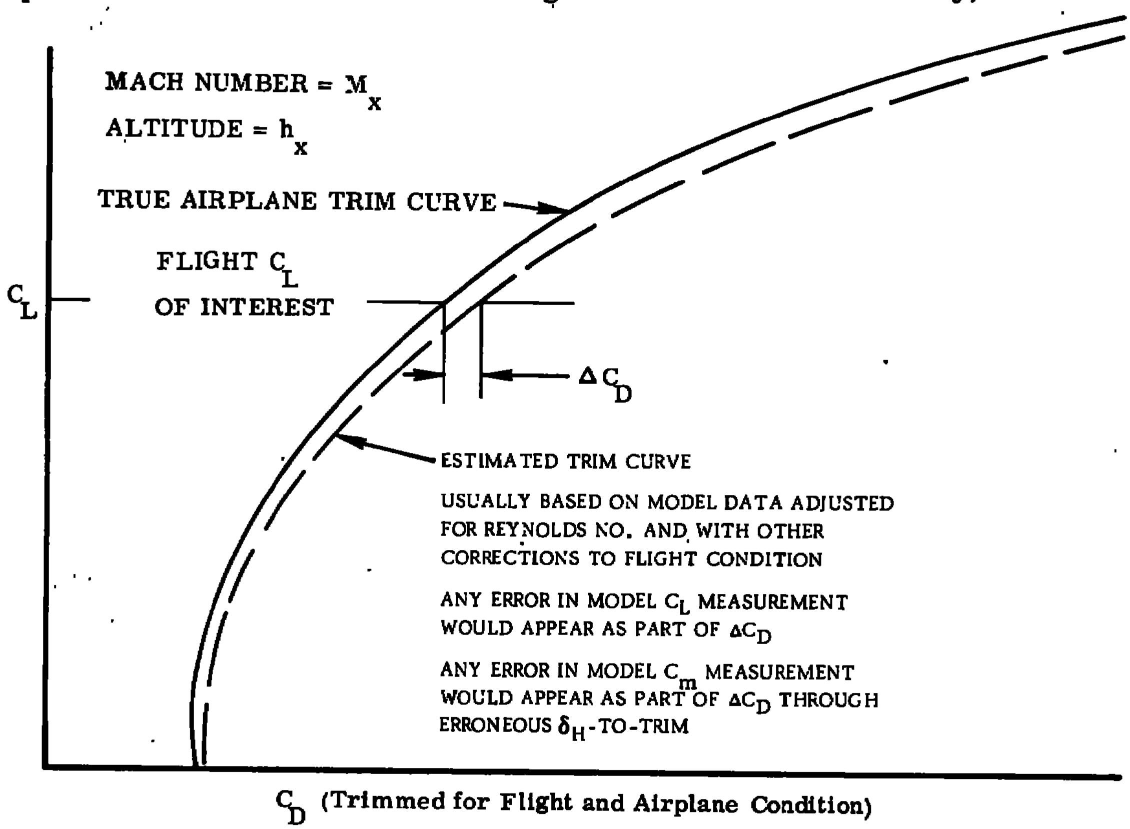


Figure 2. True Airplane and Estimated Trimmed Drag Polars

pitching moment can be corrected in flight by moving the appropriate control surface to trim, but only at the penalty of drag due to trim. For example, on the F-111, a center of pressure error of 10 percent MAC would result in a trim drag error of 0.0012. It is possible for a moment error to have other secondary effects. For example, a moment slope error would have a direct effect on the aerodynamic center calculation and thereby change the range of allowable c.g. travel.

Examples of the effect of drag error on typical missions are shown in Figures 3 and 4. The effect of an error of $C_D = 0.0010$ on various segments of a bombing and ferry mission for a typical fighter aircraft are shown. It is obvious that such an error would be very significant, particularly in the case of the bombing mission where the sea level dash distance capability is affected by drag during outbound and inbound legs of a mission having constant total radius. In other words, to deliver a bomb at a given distance from the base, drag errors in the inbound and outbound legs can "make or break" the dash distance required for an aircraft guaranteed performance goal in a design mission. For the case shown in Figure 3, a $\Delta C_D = 0.0010$ in each mission segment would result in a 23.8 percent loss in the sea-level dash distance, while maintaining a constant total mission distance. For the ferry mission illustrated in Figure 4, the range penalty due to $\Delta C_D = 0.0010$ is 3 percent.

Table 1 presents similar data on the impact of data error on the estimated performance of another fighter aircraft. Again, errors in performance data have a significant impact on a number of operating parameters. In this table the effect of lift error is considered in determining sustained turn rate, since this maneuver is performed at constant thrust or drag.

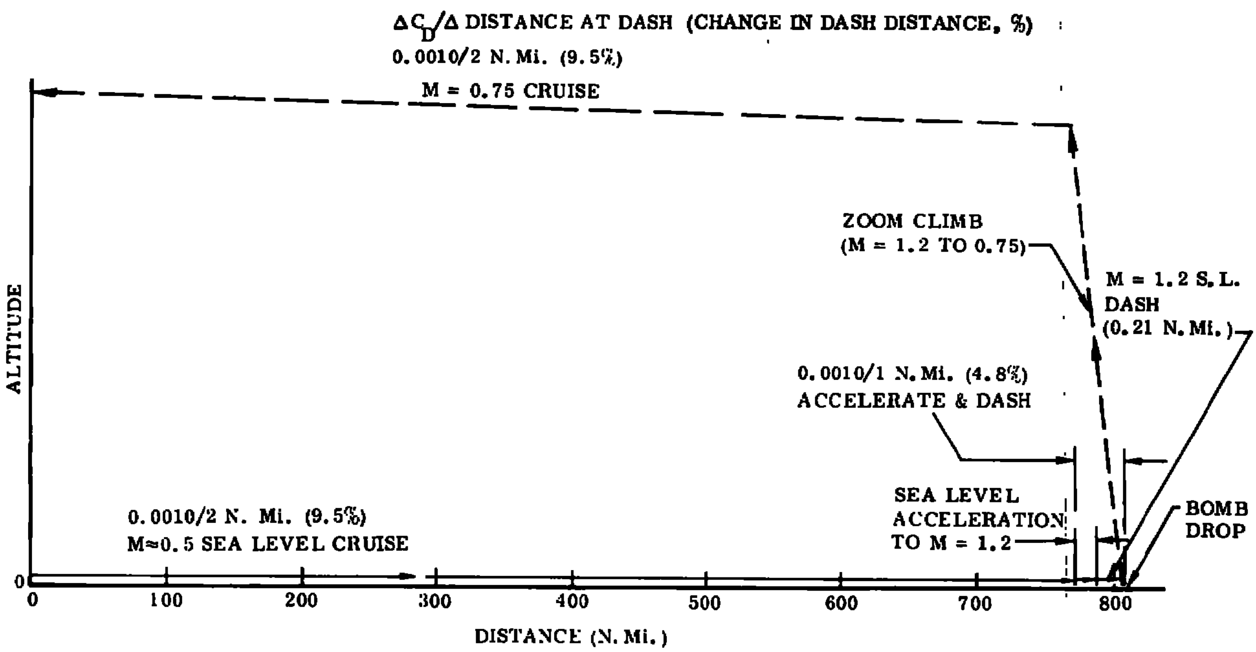


Figure 3. Typical LO-LO-HI Bombing Mission for Airplane "A"

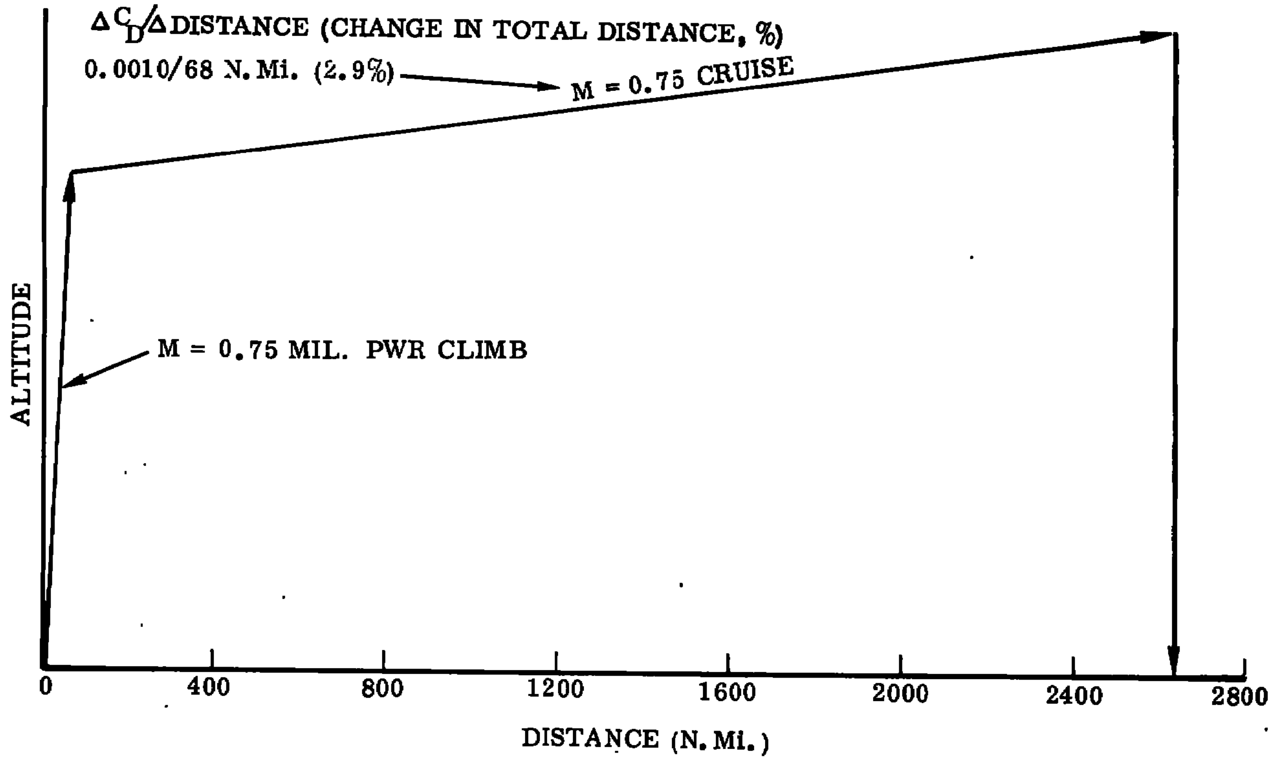


Figure 4. Typical Ferry Mission for Airplane "A"

Others have developed a requirement to measure drag to ±0.0001 (Reference 2). This seems to be a reasonable goal based on the above analysis. However, as the results of this study and others have demonstrated, even conventional wind tunnel facilities fall short of this goal.

Table 1. Performance Characteristics for Typical Fighter Airplane

MISSION RADIUS:
ΔC_D = 0.0010, 12 n. mi. (3.3%) subsonic
5 n. mi. (1.4%) supersonic
ACCELERATION TIME:
ΔC_D = 0.0010, 0.1 sec subsonic
1.5 sec supersonic
180-DEGREE TURN TIME:
ΔC_D = 0.0010, 0.011 sec (0.55%)
ΔC_L = 0.0100, 0.274 sec (1.4%)
MISSION FUEL WEIGHT:
ΔC_D = 0.0010, 55 lb subsonic (0.6%)
33 lb supersonic (0.36%)
FERRY RANGE: (SUBSONIC)
ΔC_D = 0.0010, 60 n. mi. (2.3%)

2. L. E. Ring and J. R. Milillo, "Transonic Testing — A Review," AIAA Paper 70-580, 18 May 1970.

SECTION II

METHOD OF STUDY

2.1 APPROACH

The study of the HIRT data precision centers around the point separating the similarities and contrasts of HIRT and other operating wind tunnels. Where HIRT is similar to other wind tunnels, existing information regarding the precision of current transonic wind tunnel data can be used to infer what the precision of HIRT will be in those areas. Where a wide disparity exists between HIRT operating conditions or techniques and those in other facilities, then precision estimates must be based on theoretical analysis and applicable empirical results. Therefore, any overall evaluation of HIRT data precision will be a summation of the information gained in both of the areas of similarity and contrast.

This study was divided into two parts. First, a general estimate was made of the data precision from currently operating wind tunnels. Second, an evaluation was made of the expected HIRT data precision and compared with the data precision of the existing facilities. The assessment of data precision in each case was limited to data typically obtained in static force tests of airplanes.

The study focused on factors that could be evaluated quantitatively. Thus a number of factors have not been included because of the difficulty in evaluating their contribution in a quantitative sense. An example is wall interference. The mechanism of wall interference is dependent on the specific model configuration, the wall configuration, and the wall suction. These factors are present in all wind tunnels and therefore are not critical to an inter-facility comparison.

A number of HIRT procedures or techniques will be similar to those in existing wind tunnels. It is assumed that HIRT accuracy in these areas will be equal to or better than that in existing facilities. Therefore the study method was to divide the analysis of accuracy into two broad categories: (1) wind tunnel operational characteristics or procedures common to both HIRT and existing conventional wind tunnels, and 2) characteristics unique to the HIRT facility that are likely to have an impact on overall data accuracy.

Errors in the first category were evaluated from responses to a questionnaire prepared specifically for this study. This questionnaire was used to establish a baseline representing the accuracy that can be expected from leading transonic test facilities in the United States. These participating facilities were:

General Dynamics	4-foot High Speed Wind Tunnel
NASA-Langley	8-foot Transonic Wind Tunnel
NASA-Ames	11-foot Transonic Wind Tunnel
AEDC	16-foot Wind Tunnel
AEDC	4-foot Wind Tunnel

The scope of the questionnaire was limited to questions asking information about the precision of transonic airplane test data. The responses to the questionnaire are summarized in Section III.

Error sources related to areas of operation unique to HIRT were analyzed using theoretical procedures backed up by experimental data where appropriate. Fortunately a similarity exists between HIRT operation and that currently employed at the General Dynamics High Speed Wind Tunnel (GD/HSWT). The GD/HSWT is an intermittent, pressure-driven wind tunnel with a Mach number range of 0.5 to 5.0. Using the 1- × 4-foot-high Reynolds number two-dimensional insert, the wind tunnel can be operated at 140 psia stagnation pressure. Run times are typically less than ten seconds. To support this type of operation, the GD/HSWT is currently using sophisticated data acquisition techniques close to those required for HIRT (see References 3 and 4). Therefore estimated errors in the second category could, in most cases, be partially substantiated by empirical studies specifically conducted for that purpose in the GD/HSWT.

2.2 FACTORS AFFECTING DATA PRECISION

The assessment of errors from the two categories described above was used to predict HIRT data precision. Data accuracy in a wind tunnel is based on the total of a large number of interrelated factors (Figure 5). A particular facility produces a flow environment with a certain quality of flow. This flow environment is calibrated apart from model considerations, and the calibration is used to reduce and correct the observed model data. Poor quality flow or errors in calibration have a direct effect on final data precision. The model is introduced into this flow environment and may modify it by its presence (interference). Model attitude (α or ϕ) must be determined relative to the flow direction and is a particularly critical measurement. Forces and pressures are measured on the model that may be affected by extraneous factors such as temperature shifts, pressure lag, model dynamics, and support interference. All these

3. Staff, "High Speed Wind Tunnel Facility Manual," General Dynamics/Convair Aerospace Division, October 1969.

4. W. H. Lowe, "Calibration of the General Dynamics High Reynolds Number Two-Dimensional Test Section Using a NACA 0012 Airfoil Section," General Dynamics/Convair Aerospace Division, to be published.

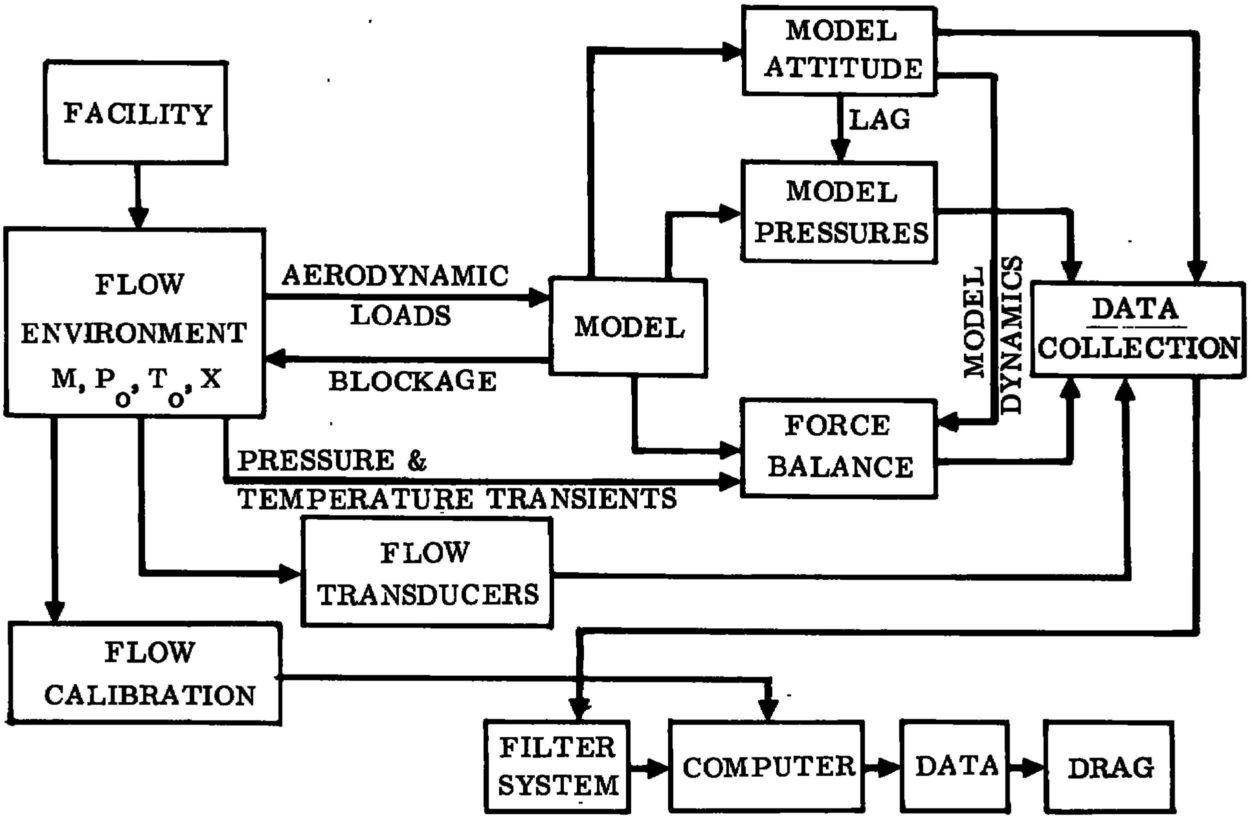


Figure 5. Data Flow Diagram

measurements are in turn affected by the accuracy of the data collection system. Finally, the process by which the data is input to a computer to obtain the final coefficients may also affect the accuracy. This entire process has many opportunities for introducing error in the final result.

The flow diagram shown in Figure 5 has been used as a guide to isolate and analyze the precision of the data components, which must be combined to obtain the drag value.

SECTION III

CURRENT WIND TUNNEL ACCURACY CAPABILITY

3.1 EARLIER STUDIES

Only limited work has been done on wind tunnel accuracy studies in the past. Most of this work was limited to computations of the estimated accuracy of single data components, presentations of data repeatability, or tests involving standard calibration models (i.e., the AGARD series). However, several sources deserve special mention. Brown and Chen (Reference 5) performed a general analysis of wind tunnel accuracy and the impact of that accuracy on aircraft performance estimation. Their work indicates that data accuracy is a problem involving the force balance, the flow uniformity, and wall support interference. Great care must be taken in all these areas to ensure that the resulting data are adequate for performance projections. The final accuracy is a function of the interaction of all these factors at the particular time of data recording.

The only adequate means for analyzing this interaction is a statistical treatment. Reference 1 develops the equations that relate the interdependence of the various factors. It is evident that the most complex measurement generally attempted in a wind tunnel is aircraft drag. This component is generally more sensitive to variation in the interaction factors mentioned. It has been noted before that drag is also the most critical factor in aircraft performance. Axial force is the most difficult of the components to measure on a strain gage balance. It is subject to buoyancy and wall interference corrections. It is also most sensitive to support interference. Therefore if one has taken all the precautions to measure the drag component accurately, it is likely that other related measurements also will be accurate.

The accuracy problem requires constant vigilance. A factor that is not critical for one model and flow condition may be very critical for another. This fact is highlighted in several experimental studies of inter-facility correlation. Treon et al (Reference 6) evaluated the correlation of data from three major transonic wind tunnels. In their study, a single model with balance was tested under identical conditions in the three wind tunnels. This program was conducted with great care to

5. Clinton E. Brown, and Chaun Fang Chen, "An Analysis of Performance Estimation Methods for Aircraft," NASA CR-921, November 1967.
6. S.L. Treon et al, "Further Correlation of Data from Investigations of a High-Subsonic-Speed Transport Aircraft Model in Three Major Transonic Wind Tunnels," AIAA Paper 71-291, 10 March 1971.

ensure the model was identical in each test. Therefore the results give an unusual insight into the problems associated with obtaining accurate aerodynamic data in wind tunnels. Of particular interest is the role of procedure in determining the quality of results.

Experience with several procedural problems in the early stages of this study (Reference 6) led the authors to conclude ". . .there is added evidence that customary test techniques, instrumentation, calibrations, and data correction practices must be critically reviewed and probably revised in order to provide the quality of wind tunnel test results required for design and development of current and proposed aircraft. Additionally, the experience of procedural errors during the reported tests acutely emphasizes the need for extreme care in the preparations and procedures associated with wind tunnel investigations." It is apparent that the diligence of the operating personnel is a major factor in wind tunnel accuracy apart from the characteristics of a particular facility.

The conclusion of this correlation study was that the best agreement that can be expected for static aerodynamic data with present instrumentation and current test procedures is as follows (C_N assumed to be the independent variable):

C_A ± 0.0005

C_{A_D} ± 0.0003

C_D ± 0.0005

C_m ± 0.0015

α ± 0.04 degree

It has been noted above that the drag component is the most difficult to measure accurately. It is evident from these correlation studies that it is also the component that most falls short of meeting accuracy requirements. Therefore factors that are most sensitive in the drag measurement are those which should receive the most attention in a new facility design and calibration.

3.2 SUMMARY OF DATA ACCURACY QUESTIONNAIRE

A questionnaire was sent to five transonic wind tunnels to establish a baseline from which the predicted accuracy of data obtained in the proposed HIRT could be compared. The responses to the questionnaire were analyzed and the results are presented below.

The questionnaire format basically reflects the data flow diagram shown in Figure 5 and was divided into three main sections: description and operational characteristics, hardware accuracy and experimentation techniques, and overall accuracy estimates. Although questionnaire sections were not specifically identified by these headings, they were chosen to be more appropriate for this summary.

Any questionnaire used to assess the wind tunnel data accuracy will have shortcomings and this questionnaire is no exception. The main problem in acquiring information about the accuracy of any measurement system is the form used to describe system or component accuracy. It was recognized that the form of the accuracy data that was readily available would probably vary from wind tunnel to wind tunnel. Therefore, to ensure a maximum response to the questionnaire, accuracy data were solicited in several common forms; i.e., standard deviation, mean error, and maximum error. The responses used one or more of these forms coupled with the descriptive phrase ". . . . percent of reading or percent of range." To reduce these many forms to a common term was indeed perplexing. Most responses were in terms of one standard deviation of full range. Therefore, quoted accuracy figures using other terms were adjusted to agree with this one form. The spread in accuracy values between wind tunnels was small once a uniform accuracy description was used. Any significant differences in accuracy are noted in this summary.

3.2.1 Description and Operational Characteristics

The description and operational characteristics for the participating wind tunnels are given in Table 2. The operating ranges shown are based on common ranges of operation and not on capabilities. That is, they do not include extreme operating conditions that may only be rarely used.

All participating wind tunnels are basically transonic facilities with a Mach number range from subsonic to low supersonic velocities.

Other supporting information provided by these facilities indicated that computer control of tunnel settings is not generally used, although the General Dynamics High Speed Wind Tunnel (GD/HSWT) has initiated a program to convert all tunnel control operations to a computer controlled system. Computer controlled operation allows all tunnel settings to be monitored and verified automatically including those that are critical for data verification. Critical tunnel settings are defined as those which, if erroneously set, would not be easily detectable in the computer test data.

3.2.2 Hardware Accuracy and Experimental Techniques

The data from the questionnaire were combined to produce a composite picture of current test practice. Where any one facility deviated significantly from this composite, these deviations were noted. Respondents were asked to consider a hypothetical test of a transonic ducted airplane model, so that all responses to the questionnaire would be on a common basis.

Table 2. Summary Description of Participating Wind Tunnels

Parameter	AEDC 4T[1]	AEDC 16T[2]	NASA-ARC 11 Ft[3]	NASA-LRC 8 Ft[4]	GD/Convair HSWT[5]
Type	Continuous	Continuous	Continuous	Continuous	Blowdown
Test section size	4 x 4 ft	16 x 16 ft	11 x 11 ft	7.10 x 7.10 ft	4 x 4 ft
Test section length	12.5 ft	40 ft	22 ft	12.3 ft	10 ft
Wall configuration	Inclined hole, variable porosity, 0% to 10%	Inclined hole, 6% porosity	Porous slot	Slotted top & bottom walls; solid side walls	Normal hole, 22% porosity
Test section plenum suction	Max. 10% flow by 4 ft pipe at front end of plenum	Max. 26% flow at rear end of plenum	Max. 0.6% flow with auxiliary pump'g system	Max. 3.5% flow with auxiliary pump'g system	Max. 10% flow with main drive ejector system
Nozzle:	Fixed	Flexible plate	Flexible plate	Fixed	Flexible plate
Surface roughness	50 μ in.	63 μ in.	10 μ in.	N. A.	50 μ in.
Maximum slope error	0.02 deg	0.025 deg	N. A.	N. A.	0.05 deg
Settling chamber contraction ratio	9.62	9.29	9.9	20.25	10
Mach number control method $M < 1$	Tunnel pressure ratio + plenum suction	Stator blade adjustment + plenum suction	Compressor speed	Compressor speed	Sonic control flaps downstream of test section
Dynamic pressure control method	Stagnation pressure + Mach number	Stagnation pressure + Mach number	Stagnation pressure	Stagnation pressure	Stagnation pressure
Reynolds number control method	Stagnation pressure + temperature	Stagnation pressure + temperature	Stagnation pressure	Stagnation pressure	Stagnation pressure
Common operating ranges:					
Dynamic pressure	50 to 1240 psf	75 to 110 psf	213 to 1986 psf	90 to 900 psf (M - 1)	200 to 2500 psf
Total pressure	400 to 3400 psfa	200 to 3750 psfs	1080 to 4600 psfa	210 to 2450 psfa	1440 to 8650 psfa
Reynolds number	10^6 to 6.6×10^6/ft	0.2×10^6 to 6.5×10^6/ft	3×10^6 to 8×10^6/ft	0.41×10^6 to 47.3×10^6/ft	2×10^6 to 15×10^6/ft
Test section static pressure	150 to 3300 psfa	100 to 3000 psfa	332 to 3600 psfa	111 to 1295 psfa	865 to 7200 psfa
Angle of attack	-11 to 28 deg	± 11 deg	-10 to 25 deg	-15 to 25 deg	-10 to 22 deg

(1) Most critical tunnel settings manually set and automatically verified for each run or change.

(2) Most critical tunnel settings manually set and verified by same person who set them originally. Most settings are documented.

(3) Most critical tunnel settings manually set and verified by same person who set them originally.

(4) Insufficient information.

(5) Most critical tunnel settings manually set; some are computer controlled. Most settings automatically checked although some settings are not verified.

The estimated accuracy for each element in the data flow path is also given. These data are supplied to substantiate the overall accuracy assessments. One notable exception: no error estimates are given for the wall corrections that may be applied to the measured aerodynamic coefficients. However, the overall accuracy estimates given in Table 5 include, in part, errors associated with wall interference (see Section 3.2.3, "Overall Accuracy Estimates"). A summary of hardware accuracy is given in Table 4.

Stagnation pressure

Stagnation pressure is measured at the settling chamber using from one to eight pressure probes. It is assumed that the circuit losses are negligible between the stagnation pressure measuring station and the model. This assumption was verified by one facility. The stagnation pressure measuring system is pneumatically damped to about 1 Hz. Accoustic measurements made in the settling chamber indicate that the predominant frequency is above 1 Hz and has a rms level between 0.1 and 0.5 percent of stagnation pressure.

The continuous wind tunnels use a self-balancing mercury manometer to measure stagnation pressure. The blowdown wind tunnel uses force-balance transducers for this measurement. Based on extensive calibration tests and error analysis, it is estimated that the manometer or transducer accuracy of stagnation pressure is within $\pm$ 0.5 psf.

Test section static pressure

Test section static pressure is measured inside the test section plenum chamber. This system is pneumatically damped. Acoustic measurements made in the plenums of two facilities indicate that the predominant frequency is above 2 Hz with a rms level equal to 1 percent of test section static pressure.

Because of the test section wall pressure drop, a difference exists between the plenum and test section static pressures. Correction factors are determined from calibration tests using a multitube centerline static pressure probe. No corrections are made to the local static pressure measurement for the orifice edge form, although one facility reported that the orifices are inspected for surface flaws. The plenum static pressure correction factor may be a function of model station, Mach number, stagnation pressure, and tunnel control settings.

Based on extensive calibration tests and error analysis, it is estimated that the manometer or transducer accuracy of static pressure is within $\pm$ 0.5 psf. Centerline calibration data have shown that the standard deviation of Mach number is between 0.001 and 0.003.

Stagnation temperature

Stagnation temperature is measured using thermocouple temperature probes located in the settling chamber. Usually more than one probe is used. The temperature range is between 40° F and 140° F. No radiation or stem velocity correction factors are applied to the temperature measurement, although the stem velocity may be 100 fps. One facility uses a shrouded probe for stagnation temperature measurements.

Based on manufacturers' specifications and facility calibration data, it is estimated that the stagnation temperature is measured within ±1° to ±3° F.

Angle of attack

Model angle of attack is usually not a direct measurement at the model, although one facility uses electrolytic bubbles located inside the model as a point reference. Correction factors are applied to the direct measurement of model support attitude. These factors consider balance and sting deflections caused by tare and aerodynamic loads and main stream flow inclination.

The support angle of attack transducer (potentiometer) is calibrated frequently using an inclinometer. These calibration results indicate that the support angle of attack should be measured within ± 0.01 degree; however, one facility reported an error of ± 0.05 degree.

Balance and sting deflection constants are determined during the static load calibration period. Three facilities reported that these constants were checked during each installation by hanging weights on the model. These constants are known within ± 0.02 to ± 0.05 degree.

Flow inclination angles are usually evaluated by making upright and inverted model runs during each installation period. This angle should be less than ± 0.1 degree. One facility reported measuring flow inclination angles as large as ± 0.5 degree. This angle should be known within ± 0.05 degree. One facility reported an uncertainty of ± 0.1 degree; another did not routinely apply corrections for flow inclination.

Corrections cannot be applied for play within the support mechanism. This play is usually less than 0.03 degree; however, magnitudes as large as 1 degree were reported by one facility.

Each facility uses extreme care to align the model in the tunnel. The uncertainty of this alignment for three facilities is ± 0.01 degree. Two facilities indicated that the model is leveled within ±0.05 degree.

Force balance

Model aerodynamic loads are measured by a multi-component strain gaged balance installed inside the model. The strain gage outputs are subject to corrections for intercomponent interaction. The data for these corrections are obtained by an extensive dead weight calibration during which both primary and combined loads are applied. Special apparatus and data acquisition systems are used for these calibrations. Thorough balance calibrations are made on a regular schedule.

Check loads are applied before each test, usually with the balance-sting assembly installed in the tunnel. A disagreement of 0.3 percent of full scale between calibration and check load results is generally acceptable. One facility adjusts the gage factors if the disagreement is larger than 0.5 percent of full scale. A second facility accepts deviations as large as 1.0 percent of full scale.

These balances are usually used from 50 to 100 percent of their full rated capacity. On any given test the maximum model loads, based on test Reynolds number range, may vary by 3:1.

Based on a) the uncertainties in the balance calibration, b) the acceptable deviations between installation check loads and calibration results, c) the uncertainties related to the difference between calibration and test environments, the balance static accuracy should be within ± 0.35 percent of full range. The interaction of normal force on axial force output is a major source of this error.

Model transducers

The questionnaire inadvertently omitted a few key questions about the measurement of model pressures. Therefore, the two comments immediately below reflect only the experience of General Dynamics High Speed Wind Tunnel personnel.

One transducer is used to measure the pressure at each model pressure tap.

Base and duct cavity pressure probes are mounted inside the model support system and are connected to the pressure tap by 2 to 3 feet of 0.049-inch OD stainless steel tubing.

An air dead weight tester is used as the working standard for calibrating model transducers. Model transducers are calibrated before each test. Transducer calibration data are fitted with linear or second-degree polynominal curves (based on best fit) using the method of least squares. The transducer accuracy is $\pm$ 0.1 percent of full range.

Data acquisition system

The data acquisition systems are generally in accordance with Figure 6. No single block contributes to the overall system inaccuracy more than any other block.

Data acquisition systems are calibrated on a regular schedule, usually semi-annually. Critical components are calibrated daily. By using data diagnostic procedures, the system performance is checked for each run. Two facilities verify system performance for each data point. All facilities use electronic active data filtering, although passive and integration filters are sometimes used. The nominal frequency cutoff point for the filters is 2 to 5 Hz. One facility uses second-order Butterworth filters with a 5-Hz cutoff frequency.

Most facilities use calibration resistors as a transfer standard. One facility uses a millivolt transfer standard. The data acquisition system (excluding transducers) has accuracy between ±0.03 and ±0.05 percent of full range. Data are recorded at a channel-to-channel rate, from 10 to 15,000 channels per second.

Corrections to aerodynamic coefficients

Three facilities limit the model size to avoid the need to correct the data for wall interference. Two facilities apply these corrections when applicable. One facility uses linear wall correction theory substantiated with interference-free data.

Table 3 gives the model sizing criteria currently used by the participating wind tunnels. Component hardware accuracy is summarized in Table 4.

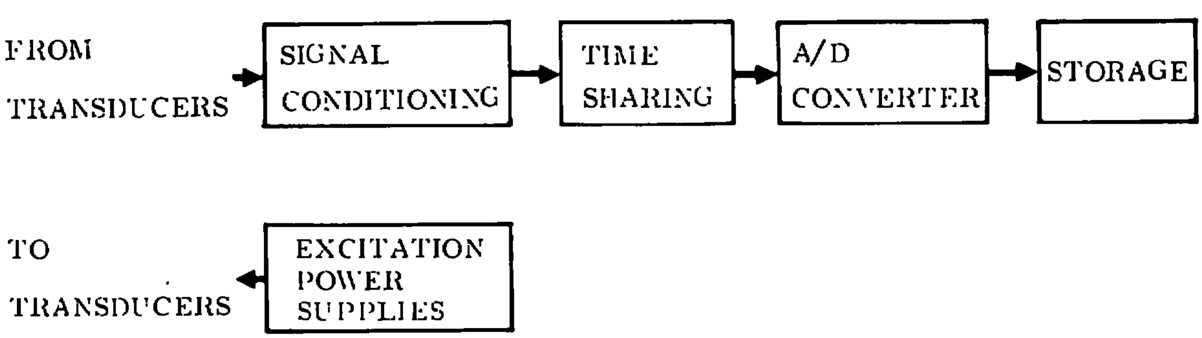


Figure 6. Instrumentation Functional Block Diagram

Table 3. Model Sizing Criteria

Parameter	Facility A*	B*	C*	D	E
Blockage (% test section area)	0.7 to 1	0.5	1	0.5	0.5
Span (% tunnel width)	50	70	75	70	60
Wing Area (% test section area)	8.5	4	8	4	5
Model length (% test section height)	0.75	0.63	1.4	0.7	1

*No wall corrections used.

Three facilities make buoyancy corrections to drag. Corrections for internal drag on a ducted model are usually based on duct pressure measurements made during calibration runs. Base pressure corrections are usually based on the total base area (model base + balance cavity).

Table 4. Summary of Hardware Component Accuracy

Component	Standard Deviation
Stagnation pressure	± 0.5 psf or ± 0.1% of range
Test section static pressure	± 0.5 psf or ± 0.15% of range
Stagnation temperature	± 1 to ± 3°F or ±2% of range
Angle of attack	± 0.06 degree
Internal balance	± 0.35% of range
Model pressures	± 0.1% of range
Data acquisition system	± 0.03 to ± 0.05% of range

3.2.3 Overall Accuracy Estimates

Each participating wind tunnel supplied estimates on their wind tunnel data accuracy, which are summarized in Table 5. The parameters listed are commonly provided as final computed data. These accuracy estimates are based on regular tunnel calibrations, instrumentation error analysis, and correlation data with other facilities. Both interference-free and wall-corrected data were used to develop these accuracy estimates. The data are given as one standard deviation errors in percent of range except where noted.

During a typical wind tunnel force run, the primary variable (angle of attack, roll angle) is systematically changed, while other flow conditions and attitude parameters are assumed constant. Actually, however, each test condition will vary from point-to-point within limits. The tolerance levels typically used to determine the acceptability of a particular run are given in Table 6. Note that the tolerance levels given for Mach number and angle of attack are nearly equal to the uncertainty of their respective measurement.

Table 5. Overall Accuracy Measurements

Parameter	Standard Deviation
Stagnation pressure	± 0.2%
Stagnation temperature	± 2°F
Static pressure (test section)	± 0.2%
Mach number	± 0.002
Dynamic pressure	± 0.5%
Reynolds number	$\pm 0.03 \times 10^6$
Angle of attack	± 0.06 degree
Drag coefficient	± 0.0005
Lift coefficient	± 0.008
Pitching moment coefficient	± 0.006

Table 6. Acceptable Tolerance Level

Parameter	Acceptable Deviation
Mach number	± 0.003
Reynolds number	1% of value
Dynamic pressure	1% of value
Angle of attack	± 0.05 degree

SECTION IV

HIRT CHARACTERISTICS THAT MAY AFFECT DATA ACCURACY

If HIRT were a conventional continuous or blowdown wind tunnel, it could be expected to achieve or better the accuracy levels noted in the previous section, since these levels represent the state of current test technology. However, HIRT has a number of operating characteristics quite different from the operation of these facilities. Therefore it is necessary to examine each of these unique characteristics to determine their impact on data accuracy. These areas are:

a. Short Run Time and Rapid Starting Process

    Pressure Measurement

    Model Sting Dynamics

    Filtering

    Data Acquisition

    Flow Field Lag

b. High Dynamic Pressure

    Balance Loads

    Aeroelasticity

c. Environmental Effects

d. HIRT Design Concept

    Flow Quality

    Contraction Ratio

Each of these areas has been examined in detail to evaluate its effect on data accuracy.

4.1 SHORT RUN TIME AND RAPID STARTING PROCESS

The run time limitations imposed by the Ludwieg-tube concept on HIRT create different problems from those in continuous wind tunnels and most blowdown tunnels. The generally accepted time available for data gathering in a HIRT run is 2.5 seconds.

The ramifications of short run times are that rapid model pitch rates, coupled with fast data cycling times, will be needed. Model pitch rates between 7 and 10 degrees per second will be required to obtain a complete drag polar in a single run. Therefore the dynamic behavior of the model-balance-sting assembly, and the model pressure measuring system, may set limits on the pitch rate to avoid degradation of data accuracy. The rapid pitch rate may require all so-called "static" model loads to be redefined as dynamic loads. Also, the time required for the flow field about the model to stabilize may limit pitch rate.

The common practice of using frequency-selective filters to reject the spurious noise in balance and transducer signals, while passing the desired ones, must also be reviewed.

The short run time period will always be preceded by very rapid changes in test section conditions (dynamic pressure, static pressure). It is apparent that any settling times associated with either the starting process or the data gathering process must be very short. These conditions also place a great premium on testing efficiency during the allotted run time. Because there are areas here with a distinct positive correlation between efficiency and data uncertainty, it is important that these tradeoffs be established.

4.1.1 Pressure Measurement Lag

Although this study is generally limited to investigation of errors that would effect force data, it is impossible to ignore totally the measurement of varying pressures. Some of the corrections applied to the computation of aerodynamic coefficients are based on pressure measurements. While some of the pressures remain essentially constant during a wind tunnel run, others may vary with angle of attack. Errors in the measurements of these varying pressures contribute to errors in the aerodynamic coefficients, and although the errors are probably small because the corrections are usually small, the order of magnitude of error should be estimated.

Pressure transducers having adequate frequency response for HIRT applications are readily available. This leaves the data acquisition system and the plumbing between pressure measurement point and transducers as possible sources of frequency distortion or lag. The data acquisition system is discussed later, bringing us to the response of the pressure tubing for treatment at this point.

Pressure tubing behaves much like a low-pass filter whose characteristics are related to factors such as tubing length and diameter. Thus the tubing tends to transmit a nonvarying pressure with no loss but tends to reduce or distort pressure variations. Continuous wind tunnels can allow the pressure to equalize throughout any pressure tubing; however, in short run time facilities, such as HIRT, it is advisable to investigate the distorting effects of the tubing on the measurement of pressures that vary with time.

Many approaches have been found for estimating the frequency response of tubing. Unfortunately, each of the analytical techniques has a particular range of pressure, length, and diameter over which the technique has been used and verified. As an example of the diversity of conclusions which can be drawn, two methods of estimating the response of HIRT pressure tubing are compared.

The analysis was performed on the error predicted for a ramp pressure change. This type of error would occur in HIRT when a pressure that varied approximately linearly with angle of attack was measured during a fast sweep of angle of attack. The principal error in this case is the result of the pressure time lag in the tubing.

The two approaches for estimating the time lag pressure error were taken from previous studies. One approach assumes the tubing behaves like an organ pipe with one end open and one end closed. The other approach bases the pressure changes on a computation of mass flow through the tubing for a constant temperature (Reference 7). The difference in magnitude of error predicted by the two approaches becomes quite significant for some typical HIRT operating conditions.

The organ pipe approach assumes the pressure transmission characteristics of the tubing are dominated by the standing wave pattern of pressure in the tube. That is, the tube is expected to resonate at that frequency for which the length of the tube is a quarter wavelength. The natural frequency was based on this assumption, and a generalized expression for damping was derived from empirical data as described in the referenced report. Thus the tube can then be represented as a second-order linear system with the following parameters:

$$f_n = \frac{C}{4\ell} \qquad \zeta = 1.4 \times 10^{-3} \sqrt{\frac{\ell}{d^2}}$$

From these parameters the lag error produced by the tube on a ramp pressure change can be derived as

$$\%\epsilon = 1.6 \times 10^{-4} \frac{\ell^{3/2}}{d^2} \frac{dP/dt}{P}$$

The mass-flow approach assumes a linear distribution of the time rate of change of pressure along the length of the tube. By using this assumption and the equation of continuity at constant temperature, it is possible to compute mass flows throughout the tube and consequently the pressure variations in the tube. This yields the following equation (Equation 26 in Reference 7).

$$\left(P_t^2 - P_m^2\right)\left(\frac{A^2}{16\pi\mu\ell}\right) = \frac{dP_t}{dt}\left(\frac{A\ell}{6}\right) + \frac{dP_m}{dt}\left(V_m + \frac{A\ell}{3}\right)$$

7. Max Kinslow, "Correction for Lag Time in Pressure Measuring Systems," AEDC-TR-58-8, August 1958.

where

P_t = pressure to be measured

P_m = pressure actually recorded by transducer

If $V_m << \frac{A\ell}{3}$ and it is assumed that for a ramp pressure $\frac{dP_t}{dt} \approx \frac{dP_m}{dt} = \frac{dP}{dt}$ after transients subside, then

$$P_t^2 - P_m^2 = \frac{8\pi\mu\ell^2}{A} \frac{dP}{dt}$$

and the pressure error $= \epsilon_p = P_t - P_m = \frac{8\pi\mu\ell^2}{A} \frac{dP}{dt} \frac{1}{P_t + P_m}$

If ϵ_p is small then $P_t \approx P_m = P$

and $$\%\epsilon = \frac{400\pi\mu\ell^2}{AP^2} \frac{dP}{dt}$$

for $\mu = 33.4 \times 10^{-8}$ lb sec/ft^2 (T = 450°R)

and $A = \frac{\pi d}{4}$,

$$\%\epsilon = 5.34 \times 10^{-4} \frac{\ell^2}{d^2P} \frac{dP/dt}{P}$$

A comparison of the percentage error expressions for the two methods indicates that, although their forms are similar, there are two key differences. The mass-flow approach error expression has an extra power of pressure in the denominator and an extra one-half power of tubing length in the numerator. This suggests that the two approaches would agree on the magnitude of error only at certain combinations of operating pressures for tubing length. The functional relationship between the two necessary for agreement is $P = 3.34 \sqrt{\ell}$.

When the pressure is higher than that given by this expression, the mass-flow approach gives a more favorable error picture than the organ pipe approach. For tubing lengths likely to be used in HIRT (ℓ < 15 ft) and for pressures likely to be measured in HIRT (P > 15 psi), the mass-flow method would predict errors lower than the organ pipe method. Extending this inference one step further, it is obvious that at higher pressures and shorter tube lengths, the two methods may differ by factors greater than ten.

Both of the above methods of lag analyses have been verified experimentally under specific conditions. The study using the organ pipe analysis, however, was concerned with conditions that more closely approximated the HIRT operation. Therefore, more weight has been placed on this analysis as representative of the pressure lag problem. However, a study that actually duplicates the HIRT operation in all respects would be helpful in further defining pressure lag at very high pressures and with high pitch rates.

Figure 7 shows percentage error in pressure measurement plotted as a function of time rate of change of the measured pressure. The error magnitudes are shown as they would be computed based on the two analyses. The pressure lag error is shown for typical tubing that might be used in HIRT. The three diameters shown are the inner diameters of standard steel pressure tubing. The 3-foot lengths are typical for connecting pressure taps to transducers located inside the model cavity, while the 15-foot lengths would represent connections from model taps to transducers in the model support mechanism.

The error shown is for an absolute pressure level of 100 psi, which might be for a wing surface pressure during an angle of attack sweep. If one assumes that a 100 psi/sec rate is equivalent to a 7 degree/second pitch rate (for example, a pressure of 300 psi at $\alpha = -2$ degrees and 100 psi at $\alpha = +12$ degrees), the pressure lag error would preclude the use of transducers other than in the model.

For pressures that change very slowly, longer lengths of tubing would be acceptable. For example, a typical HIRT model base pressure would change at 2 psi/second for a 7 degrees/second run at a 100 psi freestream static pressure. Assuming a sensitivity of C_D to base pressure of one count per psid, a 1 percent error in base pressure measurement would be necessary to cause a one-count drag error. Therefore, 15 feet of 0.02-inch tubing would not cause significant error to C_D under these conditions.

It might be concluded then that pressure instrumentation in HIRT will have to be handled on a case-to-case basis. Theoretical analysis in this area does not appear to be sufficiently developed to make accurate predictions possible. However, all available evidence indicates that pressure instrumentation for force testing (when base pressure is the critical pressure measurement) can be kept to acceptable error levels even at 7 degrees/second.

4.1.2 Model-Balance-Sting Dynamics

The principal technique conceived for obtaining transonic force data in HIRT involves the use of a model with an internal strain gage balance mounted on a tapered sting. Since this type of system cannot be made completely rigid, it is susceptible to model

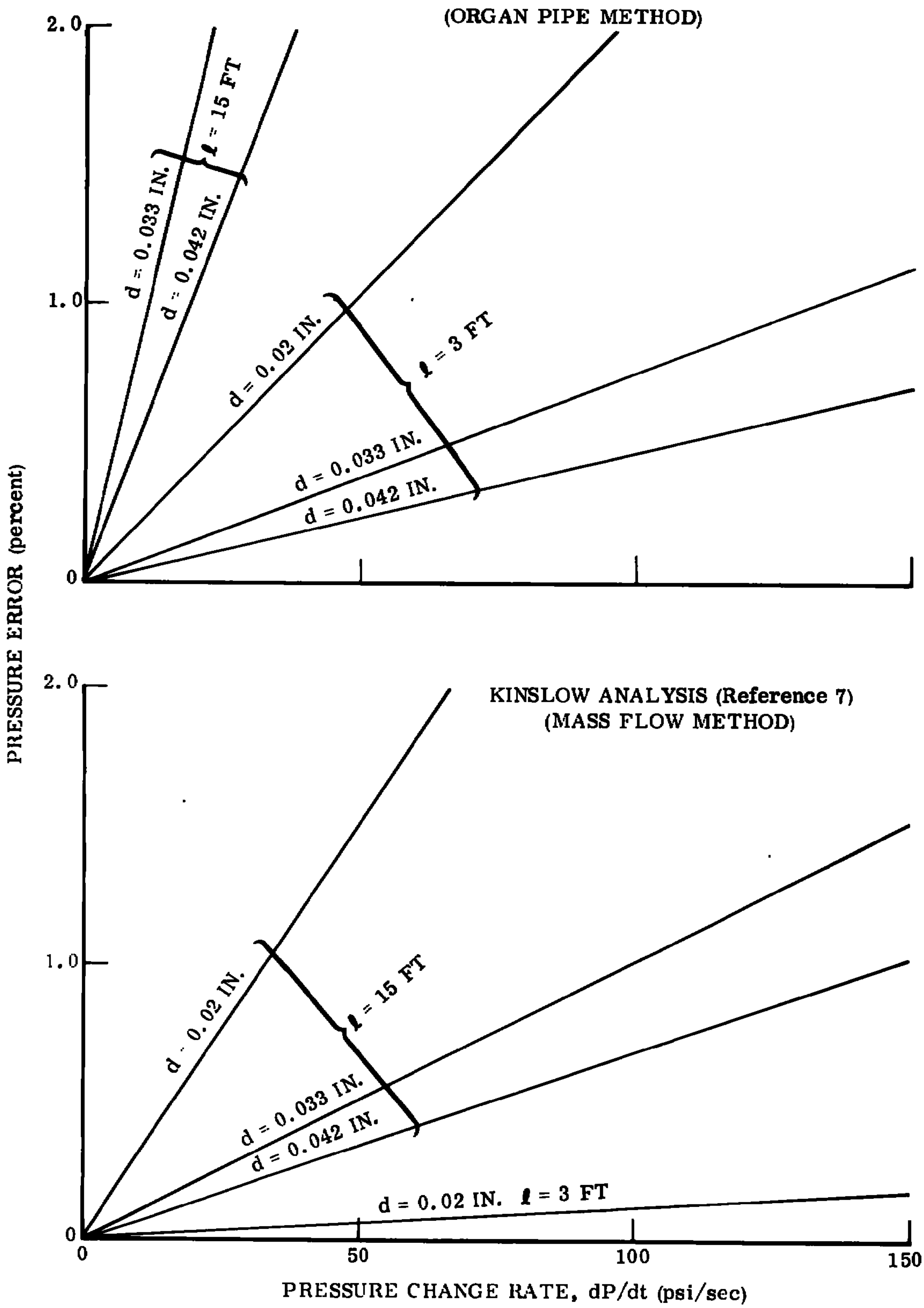


Figure 7. Comparison of Methods Used to Predict Instrumentation Pressure Tube Lag

vibrations when exposed to transient loading. These transient loads may be either aerodynamic or inertial. Two such disturbances may occur in HIRT when:

a. The tunnel flow is started with the model at an angle of attack because a large change in dynamic pressure (and consequently in model loading) occurs in less than one-half second.

b. The model-balance-sting assembly is nearly instantaneously accelerated from a fixed attitude to an angular velocity of 7 degrees per second.

These two conditions were analyzed to evaluate the possible effect of the subsequent model motion on data accuracy by using the typical Delta Canard HIRT installation shown in Figure 8. The weight, center of gravity, and mass moment of inertia of the model were approximated from scaling a typical model (Reference 8). The values obtained were 329.67 lb, M.S. = 46.12 in., and 64,310 lb-in^2, respectively. The model was assumed rigid for the analysis. The mass and stiffness properties of the balance-sting assembly are shown in Figure 8.

The frequencies and mode shapes of the first three system modes are given in Figure 9 for both the live and dummy balance. Only the first two modes were used in the analysis because the third mode has a relatively high frequency and the small slope of the aircraft centerline resulting from the third mode indicates it receives little excitation from aerodynamic forces.

The aerodynamic center of pressure was assumed coincident with the balance center. The model lift curve slope was estimated to be 0.035 per degree for a reference area of 576 in^2. The lift at zero angle of attack was assumed to be zero. Pitching moments and drag forces were neglected.

Quasi-steady aerodynamics were used. Quasi steady aerodynamics assume the instantaneous lift on the aircraft is given by the relationship

$$L = C_{L\alpha} \times S_W \, q \, (\alpha_{SS} + \alpha_D - \dot{h}/V_\infty)$$

where

α_{SS} is the nominal angle of attack

α_D is the angle of attack resulting from elastic deformation

$\dot{h}$ is the vertical (upward) velocity of the center of pressure

8. W. K. Alexander et al, "Wind Tunnel Model Parametric Study for Use in the Proposed 8 ft × 10 ft High Reynolds Number Transonic Wind Tunnel (HIRT) at Arnold Engineering Development Center," AEDC-TR-73-47, March 1973.

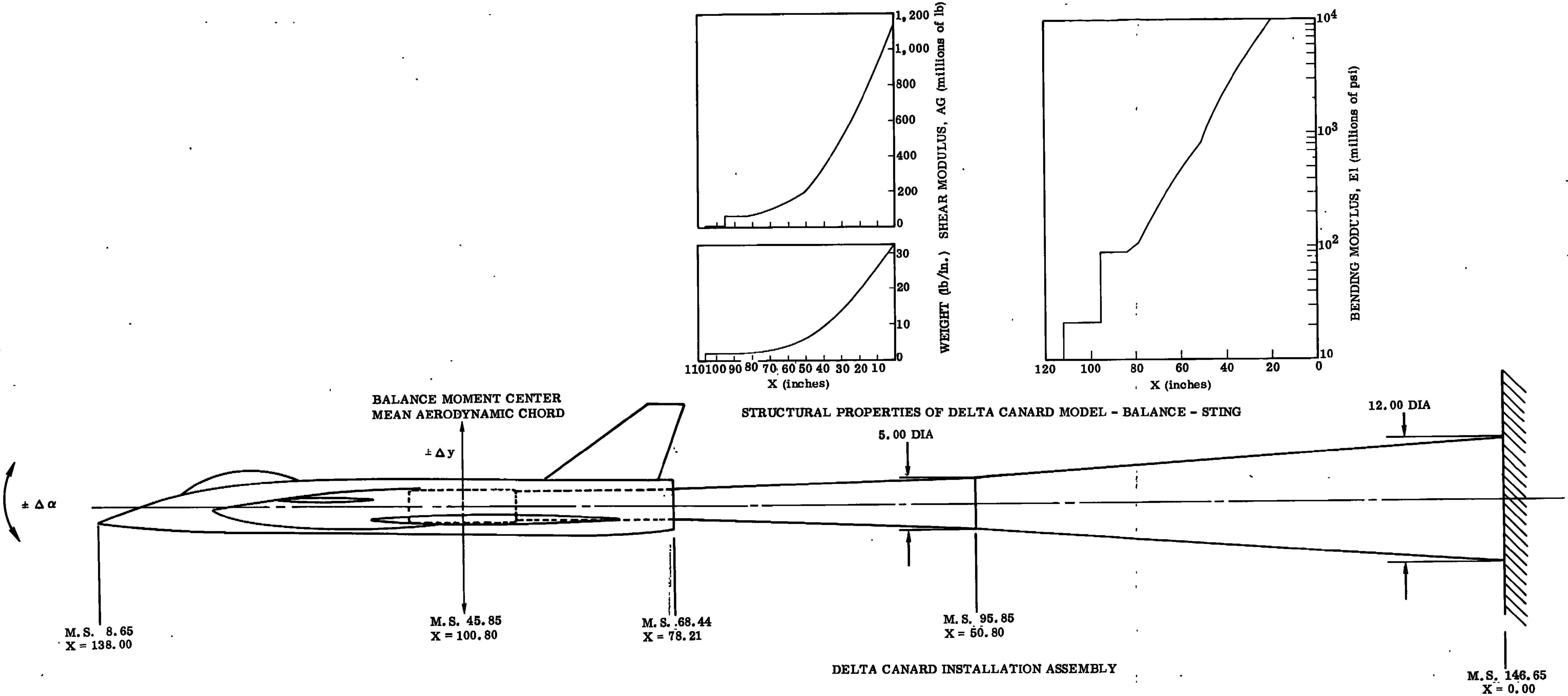


Figure 8. Typical Model-Balance-Sting Installation for HIRT

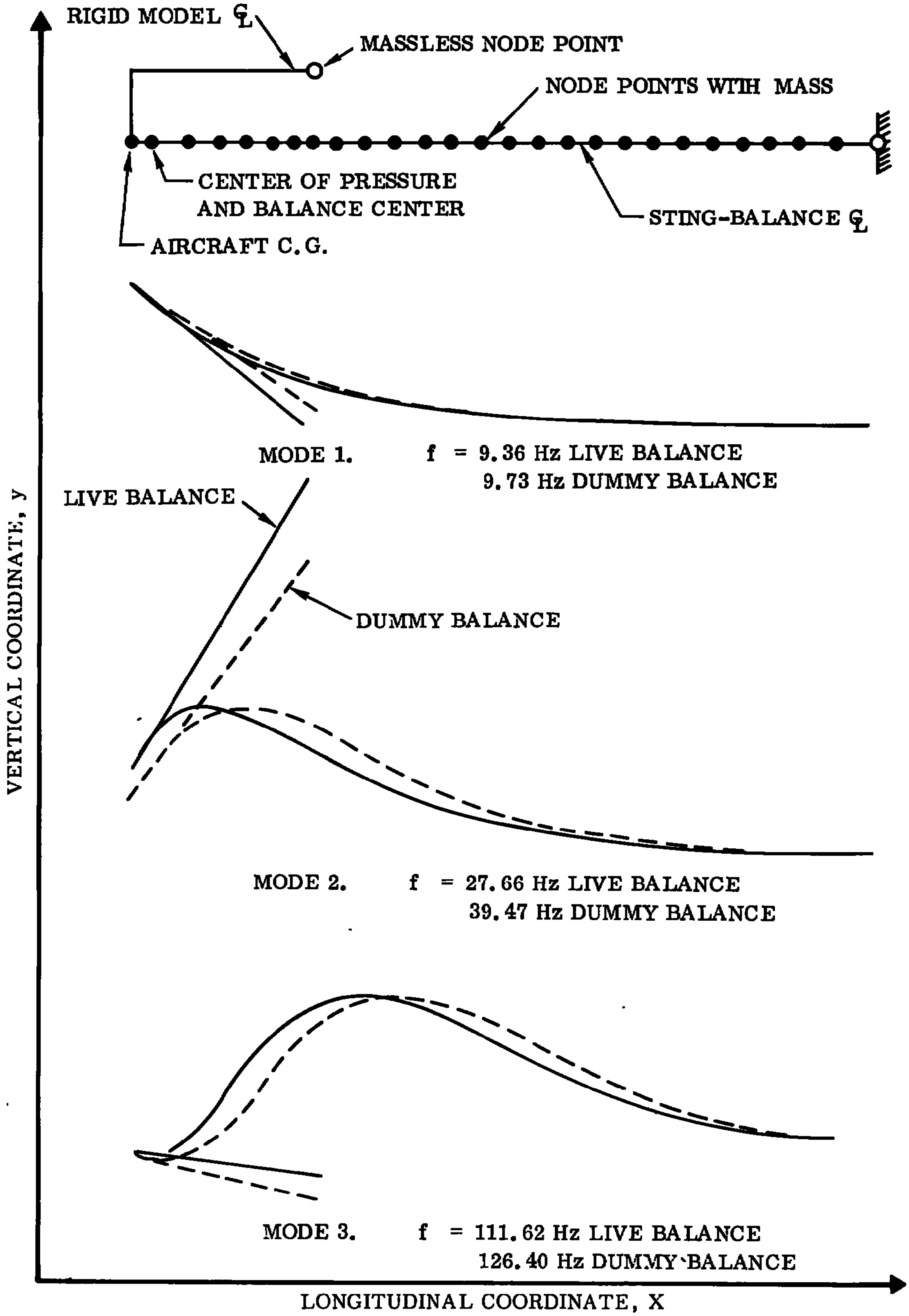


Figure 9. Dynamic Model and Mode Shapes for Delta Canard Wind Tunnel Installation

Quasi steady aerodynamics ignore aerodynamic lag effects resulting from intertia of the air, but have been both experimentally and analytically shown to be accurate when the Strouhal number, $b\omega/V_{\infty}$, is small (less than 0.5). In this equation, b is a reference length (usually wing mean semi-chord) and ω is the circular frequency of the highest elastic mode under consideration. For this model and tunnel velocity the Strouhal number is about 0.28 even when the distance between the wing and canard centers of pressure is used as a reference length.

Condition (1) was analyzed by assuming that the tunnel was started with the model at an angle of attack equal to 24 degrees. The analysis for Condition 2 assumed the angle of attack was zero between 0 and 0.5 second and increased at a rate of 7 degrees per second thereafter. Both analyses used the dynamic pressure shown in Figure 10, assumed zero structural damping, and were for the live balance.

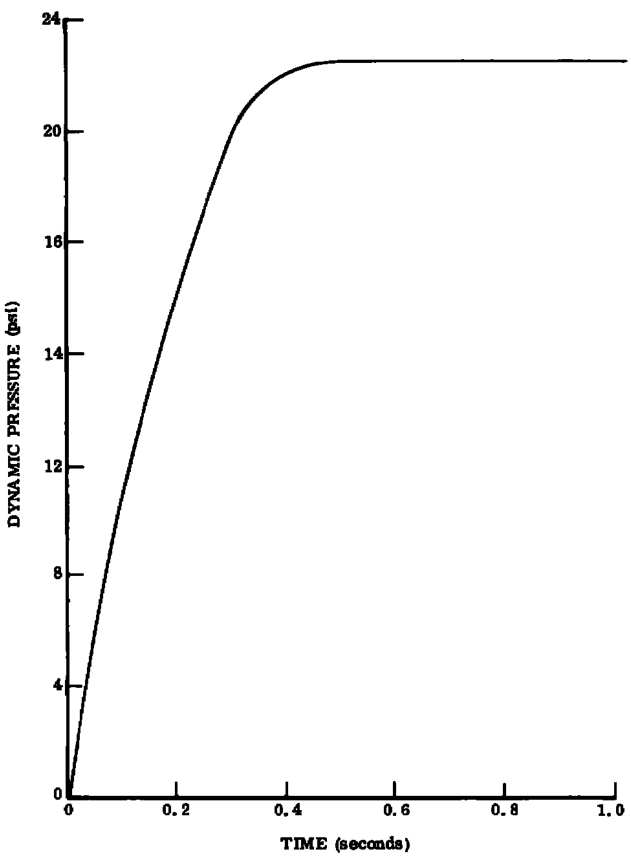


Figure 10. Estimated HIRT Dynamic Pressure History

The tunnel conditions q_{max} = 22.92 psi, T = 300°K, and Mach = 0.52 correspond to condition 23 in Table 2 of Reference 9. The results obtained in the analysis are shown in Figures 11 and 12. These figures show the translational and rotational motion of the model for the two cases analyzed.

Results for other constant angles of attack (α_n) can be determined from Figure 11 by multiplying the results shown in this figure by $\alpha_n/24$. These results can then be superimposed on those shown in Figure 12 to approximate the response from having a nonzero initial angle of attack that increases at a rate of 7 degrees per second after 0.5 second.

The damping evident in the results is from aerodynamic forces and corresponds to structural damping of C/C_{crit} $\cong$ 1 percent. Since the actual damping in a structure of this type can be expected to be considerably less than 1 percent, inclusion of structural damping would not appreciably alter the results.

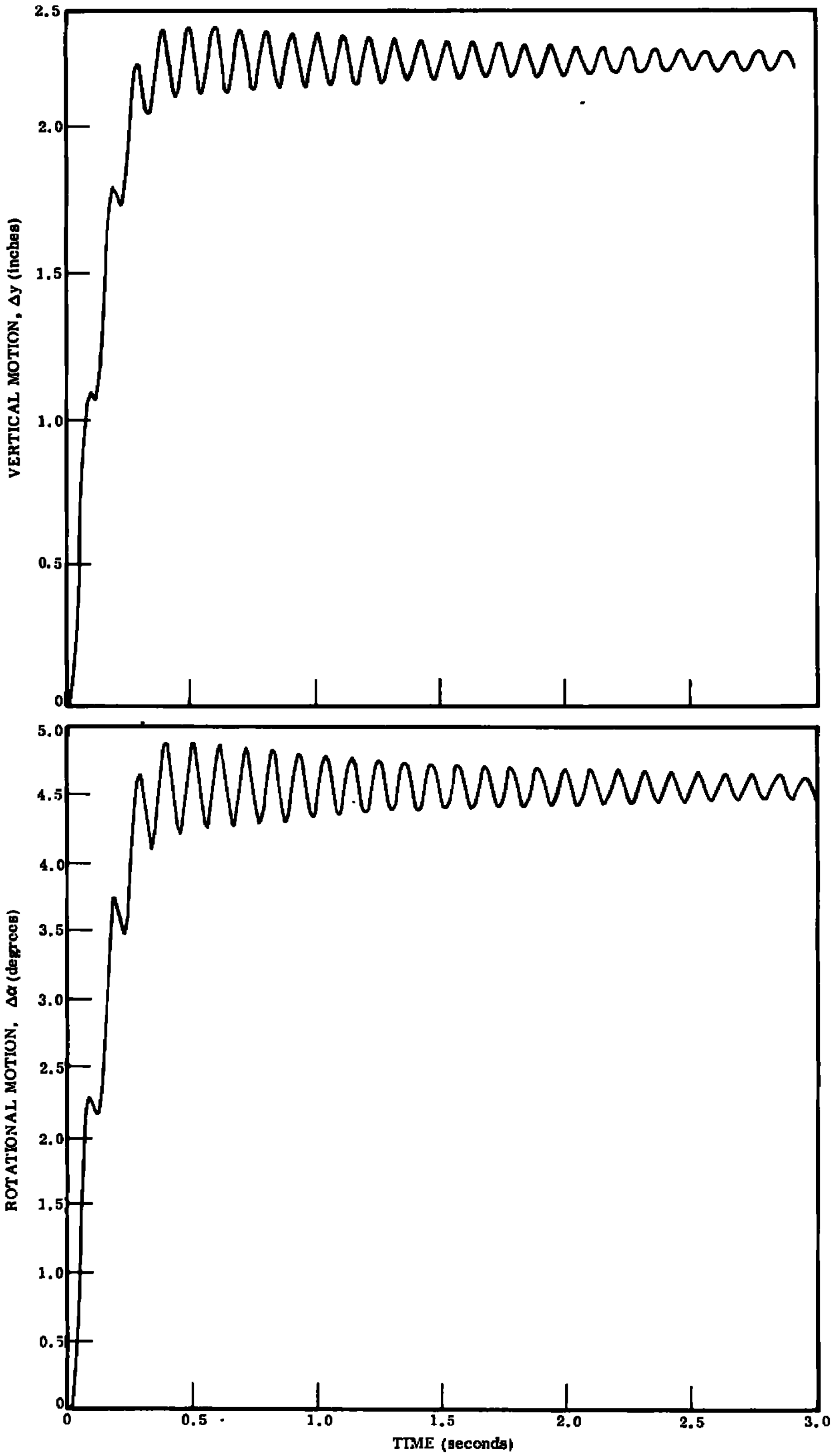


Figure 11. Motion of Delta Canard Model when HIRT is Started with Model at 24 Degrees Angle of Attack

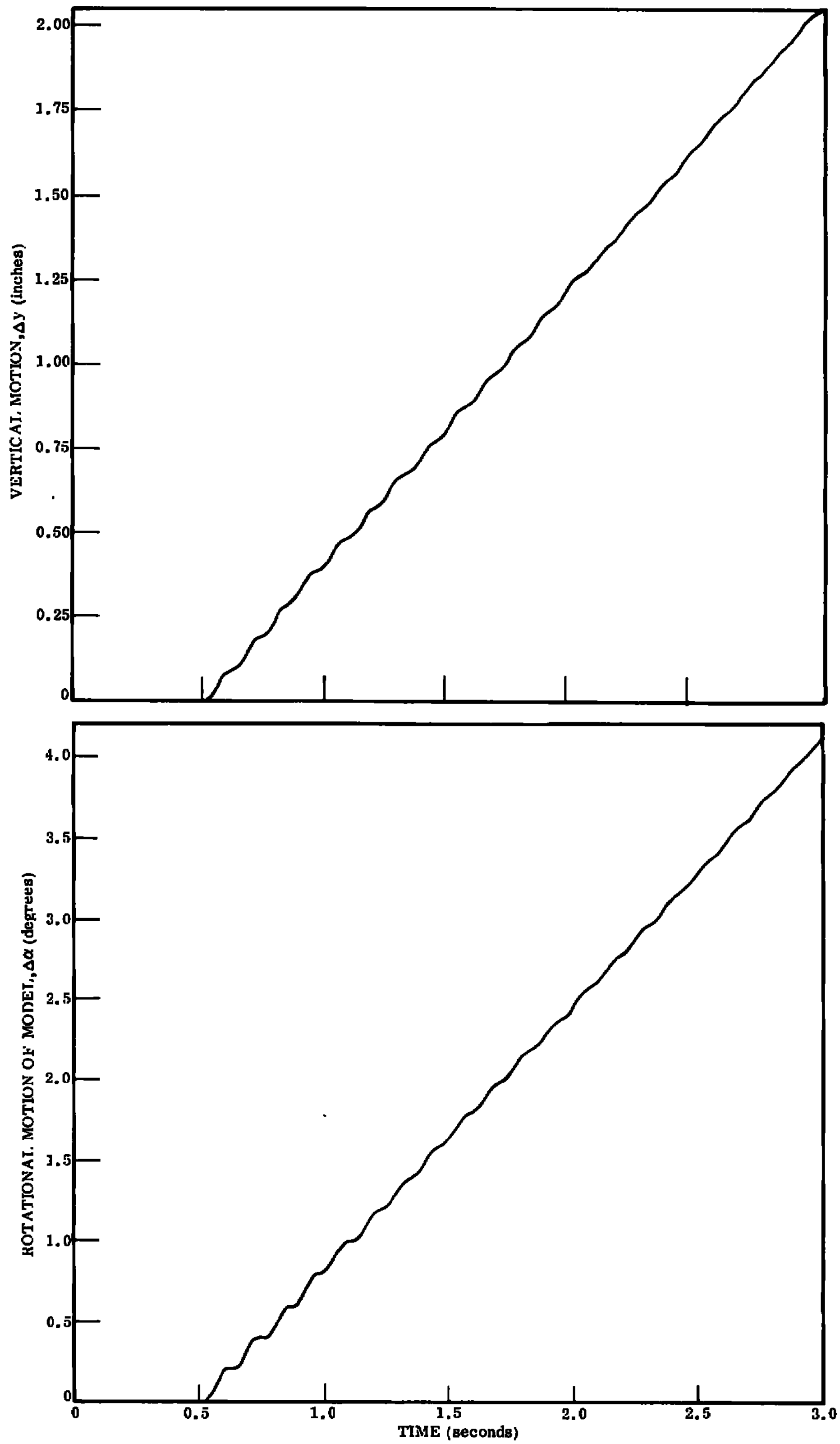


Figure 12. Motion of Delta Canard Model when Pitched at 7 Degrees per Second

Analyses using the dummy balance were not performed since the mode shapes and frequencies in Figure 9 are substantially the same for the live and dummy balances.

If the model is at a large initial angle of attack when starting HIRT, Figure 11 shows that the rapid buildup of dynamic pressure can produce sizable transient responses; i.e., vertical motion = ±0.1 inch and rotational motion = ±0.4 degree. The transient responses resulting from dynamic pressure buildup at angle of attack would persist at a fairly high level throughout the duration of the run, even if a reasonable value of structural damping was assumed.

In addition to uncertainty in angle of attack, the model vibrations predicted by the preceding analysis also create aerodynamic and inertial balance loading, which contributes to uncertainties in the aerodynamic coefficients. The fluctuating aerodynamic loads can be eliminated by filtering, since they are typically symmetrical about the mean. The magnitude of the inertial uncertainties is estimated by using the first vibration mode and by assuming that the model motion is essentially sinusoidal. The dynamic load perturbations are computed from:

$$\hat{C}_D = \hat{C}_N \sin \bar{\alpha} + \hat{C}_A \cos \bar{\alpha}$$

where

$$\hat{C}_x \sin \bar{\alpha} = \frac{x}{qS} \sin \bar{\alpha} = \frac{ma}{qS} \sin \bar{\alpha}$$

and

$$a \text{ (axial or radial acceleration)} = \dot{\hat{\alpha}}^2 R = (2\pi f)^2 \hat{\alpha}^2 R$$

$$a \text{ (normal or tangential acceleration)} = \ddot{\hat{\alpha}} R = (2\pi f)^2 \hat{\alpha} R$$

Therefore:

$$\hat{C}_N \sin \bar{\alpha} = \frac{m}{qS} (2\pi f)^2 \hat{\alpha} R \sin \bar{\alpha}$$

$$\hat{C}_A \cos \alpha = \frac{m}{qS} (2\pi f)^2 \hat{\alpha}^2 R \cos \bar{\alpha}$$

and

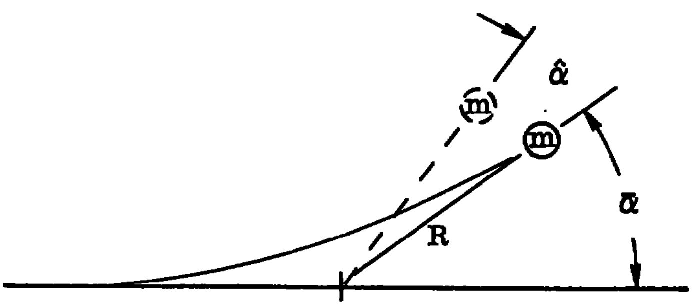
$$\hat{C}_D = \frac{m}{qS} (2\pi f)^2 \hat{\alpha} R \sin \hat{\alpha} + \frac{m}{qS} (2\pi f)^2 \hat{\alpha}^2 R \cos \bar{\alpha}$$

where

m = mass of model (slugs)

q = dynamic pressure (psi)

S = reference area (in.^{2}).



f = sting natural frequency (Hz)

$\hat{\alpha}$ = peak excursions of $\bar{\alpha}$ (rad)

R = effective radius of oscillation

$= \hat{Y} (\hat{\alpha} \cos \bar{\alpha})^{-1}$ (ft)

$\hat{Y}$ = peak excursion of Y (ft)

$\bar{\alpha}$ = average value of angle of attack during oscillations (rad)

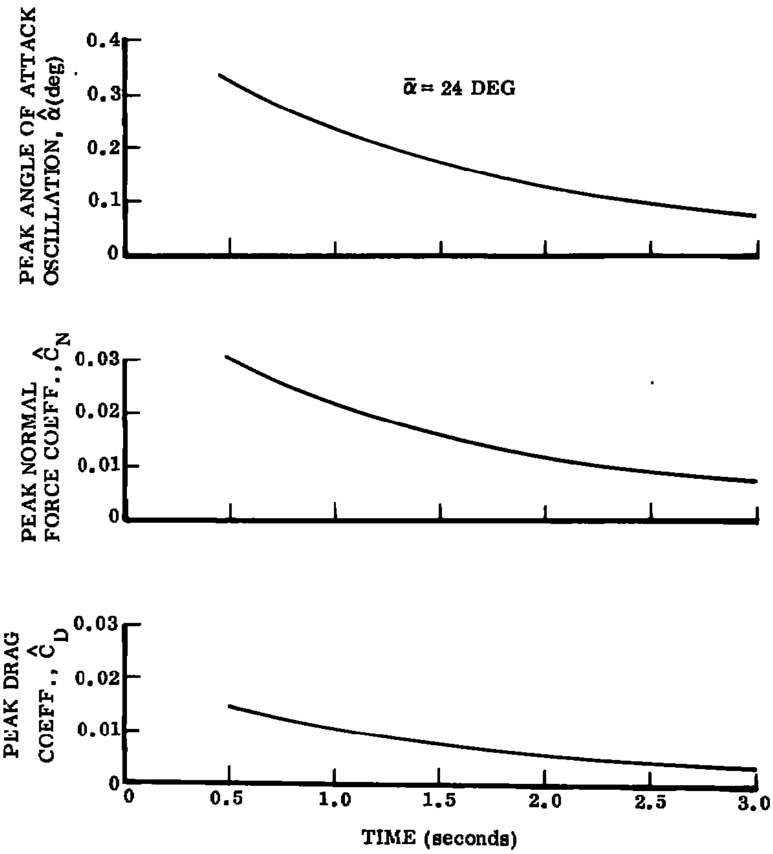


Figure 13. Peak Excursion of Model Forces and Angle of Attack Caused by Rapid Dynamic Pressure Buildup

The results of this analysis are shown in Figure 13. These calculations indicate that at the predicted vibration levels the inertially induced normal force is at least an order of magnitude greater than the axial force for the high angle of attack case. This assessment is based on an unfiltered, uncompensated set of loads, and the relative significance of axial and normal loads would probably change, at least with filtering. Filtering the axial inertial loads induced by model vibrations in the pitch plane tends to reduce the error peaks but does not eliminate the error, since the force is always in a direction to reduce axial force. This spurious drag force would persist during the entire test time of about two seconds. However, the normal force disturbances can be totally eliminated by filtering, since they are typically symmetrical about zero. These oscillations may be alleviated by using the highly damped sting design shown in Figure 14. The conventional hollow sting would be replaced with a two-shell sting with a damping material that bonds the shells together.

Figure 12 shows that the transient motions resulting from initiating model pitch are small after the test section flow has stabilized. However, these model-sting vibrations can be reduced by initiating the sector sweep using two techniques.

A simplified time-dependent functional relationship between the sting root and the model attitude and position can be approximated adequately by a second-order transfer function having a natural frequency, ω_0, and a damping factor, ζ. The resulting vibration in an underdamped sting-model combination would have a maximum value of

$$\frac{\dot{\alpha}}{\omega_0 \sqrt{1 - \zeta^2}}$$

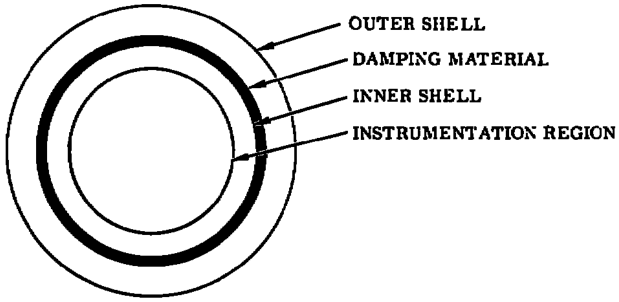


Figure 14. Highly Damped Sting Cross Section

For representative values of $\omega_0 = 2\pi$ (10 Hz) = 62.8 radians/second, $\zeta = 0.1$, and $\dot{\alpha} = 7$ degrees/second, the resulting maximum value of the oscillation would be ±0.11 degree. This motion is shown in the top curve of Figure 15, which is similar to that shown in Figure 12.

By limiting the maximum sting-drive angular acceleration at the start of the sweep to some selected value, $\ddot{\alpha}_{lim}$, the frequency content at the natural frequency of the model-sting combination can be reduced. Using the conditions specified for the nonmodified sweep start, a limited acceleration of 35 degrees/second^2 would reduce the maximum model vibration from ±0.11 to ±0.0089 degree (see center curve of Figure 15). The bottom curve shows the model motion when the α drive command signal is filtered. A first-order filter having a time constant of 0.1 second reduced the vibration from 0.11 to 0.0173 degree.

Each of these methods causes a time lag in the model attitude, which adds 0.1 second to the time required to sweep through a specified α range. However, since these methods do not create any error in the functional relationship between the aerodynamic coefficients and angle of attack, they represent an alternative to the use of heavy data filtering to remove model vibrations from the data.

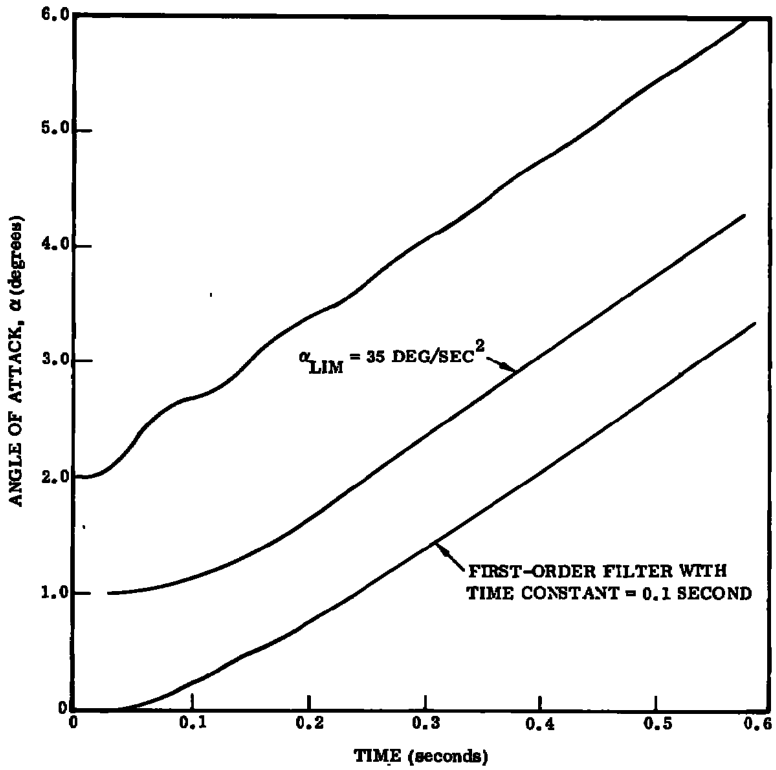


Figure 15. Model Dynamics Affected by Pitch Control Techniques

4.1.3 Filtering

When processing wind tunnel instrumentation data some form of filtering is almost universally used, usually in the form of either active or passive electronic filtering in each data acquisition channel. Sometimes this analog filtering is supplemented by some form of smoothing performed on the data during digital processing after the data are stored. Even when digital filtering or smoothing is used, however, it is usually necessary to use some degree of analog pre-filtering to remove sharp transients, which might cause overscales further along in the data processing channel.

Once the need for some degree of analog filtering in each data channel is accepted it is necessary to determine cutoff frequencies and sharpness of attenuation. In each case a tradeoff must be made between the desired attenuation of unwanted signals and the undesired response times and data distortion caused by filtering. A continuous wind tunnel can tolerate filtering sufficient to remove even the lowest frequency noise, since a settling time prior to recording a data point is part of the normal operation of such a tunnel. However, that same amount of filtering in a tunnel using a continuous sweep of parameters might easily destroy most of the information in the data.

Given the relatively short time available for data gathering in HIRT, obviously little time is available for filter settling. Consequently, where filtering is used, the distorting effect on the data must be carefully examined. In particular, the possibility of filter distortion to data taken during sweeps of independent parameters, such as angle of attack, must be considered.

In most wind tunnels, including those which take data during pitch sweeps, the instrumentation channels that handle the strain-gage balance components are filtered. The low signal-to-noise ratio typical of strain gage instrumentation generally requires some filtering to improve that ratio. Inherent in this filtering is an effective time delay, which for most filters is inversely proportional to the filter cutoff frequency. This time delay has the effect of shifting the balance component data with respect to any nonfiltered variable, such as angle of attack.

The solution (or at least partial solution) to this problem has been to shift the unfiltered variables into time agreement with the filtered variables. This is accomplished by filtering any variables functionally related to the balance loads, using filters with the same properties as those on the balance. This approach was originally suggested by S. M. Cooksey of Vought Aeronautics Corp.

The matched filtering technique, which is currently used at the GD/HSWT, has performed well in practice and can be supported in theory as long as the only effect of the filtering is to shift the data along the time axis. However, the forces measured by a wind tunnel balance while the model is pitching are functions of time and can be considered to be composed of many different frequencies. The conditions necessary for a filter to produce a pure time delay are:

a. The filter phase shift is directly proportional to the signal frequency.

b. Filter attenuation is independent of the signal frequency.

Fortunately (at least for this case) the filters typically used in wind tunnel instrumentation channels meet these two conditions as long as the signal frequency does not exceed one-tenth of the filter cutoff frequency. These conditions are met for first- and second-order filters with damping factors that do not significantly exceed unity.

Three types of filters are used for wind tunnel instrumentation data. They are shown in Figure 16 with expressions describing the data lag created by each. Prior treatments of this subject have been based on the approximate relationships shown in the right-hand column. The passive filters have been treated more completely, probably because they are in very common use in older facilities and because the mathematics are simpler. However, with the pressure to gather more data in a given run time (by pitching at a faster rate, which effectively increases the data frequencies in direct proportion to the pitch rate), the data frequencies tend to approach the disturbance or noise frequencies. The temptation then exists to attempt to remove all undesirable noise or disturbance by massive filtering and to rely on assumptions that matched filtering of all channels causes no distortion in the data, which is a dangerous assumption. Therefore a more general investigation of the errors created by filtering was undertaken. The following are the results of that investigation:

The functional relationship between α and C can be represented by a power series on α:

$$C = A_0 + A_1 \alpha + A_2 \alpha^2 + A_3 \alpha^3 + \ldots + A_n \alpha^n$$

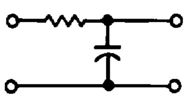
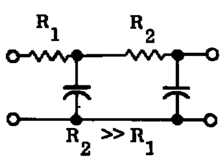
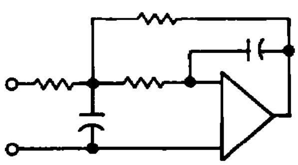
FILTER TYPE	CIRCUIT	PHASE LAG (RAD)	TIME LAG (SEC)	APPROX. TIME LAG FOR $\omega << \omega_n$
FIRST-ORDER, PASSIVE		$\tan^{-1}\left(\frac{\omega}{\omega_0}\right)$	$\frac{\tan^{-1}\left(\frac{\omega}{\omega_0}\right)}{\omega}$	$\frac{1}{\omega_0} = \frac{1}{2\pi f_0}$
SECOND-ORDER, CRITICALLY DAMPED, PASSIVE		$\tan^{-1}\frac{2\left(\frac{\omega}{\omega_0}\right)}{1-\left(\frac{\omega}{\omega_0}\right)^2}$	$\frac{1}{\omega}\tan^{-1}\frac{2\left(\frac{\omega}{\omega_0}\right)}{1-\left(\frac{\omega}{\omega_0}\right)^2}$	$\frac{2}{\omega_0} = \frac{1}{\pi f_0}$
SECOND-ORDER, LESS THAN CRITICAL DAMPING, ACTIVE		$\tan^{-1}\frac{2\zeta\left(\frac{\omega}{\omega_0}\right)}{1-\left(\frac{\omega}{\omega_0}\right)^2}$	$\frac{1}{\omega}\tan^{-1}\frac{2\zeta\left(\frac{\omega}{\omega_0}\right)}{1-\left(\frac{\omega}{\omega_0}\right)^2}$	$\frac{2\zeta}{\omega_0} = \frac{\zeta}{\pi f_0}$

Figure 16. Typical Filtering Used with Wind Tunnel Instrumentation

where C is an aerodynamic coefficient, α is angle of attack and A_0, A_1, A_2, A_3, . . . , A_n are coefficients from an n power curve fit. The second-order analog filters have transfer functions of the form:

$$F(S) = \frac{\omega_o^{\,2}}{S^2 + 2\zeta\omega_o S + \omega_o^{\,2}}$$

Filters

$$\alpha(t) \longrightarrow \boxed{F(S)} \xrightarrow{\alpha_m(t)} = \text{filtered } \alpha \text{ (measured)}$$

$$C(t) \longrightarrow \boxed{F(S)} \xrightarrow{C_m(t)} = \text{filtered coefficient (measured)}$$

where

ω_o is the undamped natural frequency

ζ is the damping factor

S is the LaPlace transform operator

The error in the filtered coefficient ($C_m(t)$) is the difference between the filtered C and the C ($C(\alpha_m)$) obtained by substituting the filtered α into the power series. (Refer to above sketch.) Error is then:

$$\epsilon = C_m(t) - C(\alpha_n)$$

The time rate of change of α is constant ($\dot{\alpha}$); therefore:

$$\alpha = \alpha(t) = \dot{\alpha}\, t$$

$$\alpha(S) = L\ [\alpha(t)] = \frac{\dot{\alpha}}{S^2} \text{ where L indicates a LaPlace transform}$$

$$\alpha_n(t) = L^{-1}\left[\frac{\dot{\alpha}}{S^2}\, F(S)\right] \approx \dot{\alpha}\left[t - \frac{2\zeta}{\omega}\right]$$

and

$$C(\alpha_m) = A_0 + A_1\dot{\alpha}\left(t - \frac{2\zeta}{\omega}\right) + A_2\dot{\alpha}^2\left(t - \frac{2\zeta}{\omega}\right)^2 + . . . + A_n\dot{\alpha}^n\left(t - \frac{2\zeta}{\omega}\right)^n$$

$$= \sum_{k=0}^{n} A_k\dot{\alpha}^k\left(t - \frac{2\zeta}{\omega}\right)^k$$

Similarly:

$$C(S) = L\,[C(t)]$$

$$C_m(t) = L^{-1}\,\{L[C(t)]\,F(S)\}$$

and

$$C_m(t) = L^{-1}\left\{A_0\,\frac{F(S)}{S} + A_1\dot{\alpha}\,\frac{F(S)}{S^2} + 2A_2\dot{\alpha}^2\,\frac{F(S)}{S^3} + \ldots + n!\,A_n\dot{\alpha}^n\,\frac{F(S)}{S^{n+1}}\right\}$$

$$= \sum_{k=0}^{n} L^{-1}\left\{k!\,A_k\,\dot{\alpha}^k\,\frac{F(S)}{S^{k+1}}\right\} .$$

Therefore:

$$\epsilon = C_m(t) - C(\alpha_n)$$

$$\epsilon = \sum_{k=0}^{n} A_k\,\dot{\alpha}^k\left\{k!\,L^{-1}\left[\frac{F(S)}{S^{k+1}}\right] - \left(t - \frac{2\zeta}{\omega}\right)^k\right\}$$

ignoring terms containing $e^{-\zeta\omega t}$

Evaluating each of the first seven terms of the series, $n=0$ to $n=6$, individually, the following results are obtained:

$$\begin{aligned}
\epsilon = \;& 2\,[A_2 + 3A_3\alpha + 6A_4\alpha^2 + 10A_5\alpha^3 + 15A_6\alpha^4]\,(2\zeta^2 - 1)u^2 \\
& -8\,[A_3 + 4A_4\alpha + 10A_5\alpha^2 + 20A_6\alpha^3]\,\zeta\,(5\zeta^2 - 3)u^3 \\
& +8\,[A_4 + 5A_5\alpha + 15A_6\alpha^2]\,(46\zeta^4 - 36\zeta^2 + 3)u^4 \\
& -16\,[A_5 + 6A_6\alpha]\,\zeta\,(238\zeta^4 - 240\zeta^2 + 45)u^5 \\
& +16\,[A_6]\,(2876\zeta^6 - 3600\zeta^4 + 1080\zeta^2 - 45)u^6
\end{aligned}$$

where

ϵ is the error in the coefficient

u is the ratio of pitching rate, $\dot{\alpha}$, to ω_0 of the filters in $\dfrac{\text{deg/sec}}{\text{rad/sec}}$

The analysis above was applied to three typical longitudinal aerodynamic coefficients obtained in the General Dynamics four-foot transonic wind tunnel. The three coefficients were pitching moment, C_m, lift force, C_L, and drag force, C_D, versus angle of attack, α.

The data from these coefficients were curve-fitted using a sixth-order, least-squares fit. The error produced in these coefficients by matched filtering was evaluated for several selected pitch rate/filter frequency ratios $\left(\frac{\dot{\alpha}}{\omega_0}\right)$ at different filter damping factors, ζ. Typical results are shown in Figure 17.

The data indicated a distinct trend toward a minimum error in the 0.7 damping factor range. This minimum was more pronounced at lower pitch rate/filter frequency ratios.

Using a damping factor of 0.707 (second-order Butterworth, Reference 9) for the filtering, the data were further analyzed to obtain the tradeoff between error introduced by the filtering and the attenuation of low frequency (10 Hz) signals (typical of sting vibrations) in the data.

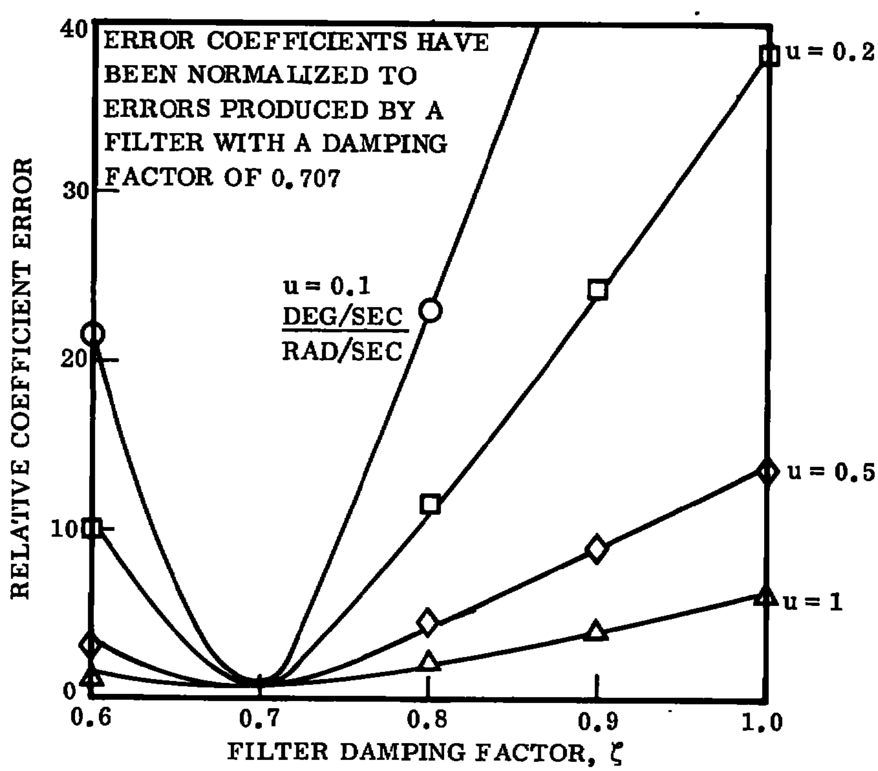


Figure 17. Effect of Filtering on Test Data

The results are summarized in Table 7.

Table 7. Aerodynamic Coefficient Errors Caused by Filters

u (N.D.)	Filter Frequency at $\dot{\alpha}$=7 deg/sec (Hz)	Max Error/Max Value C_m (percent)	C_L (percent)	C_D (percent)	Attenuation of 10 Hz Vibration
0.2	5.6	0.0042	0.016	0.018	1/3.4 (-11 dB)
0.34	3.3	0.020	0.088	0.088	1/9.4 (-19 dB)
0.5	2.2	0.059	0.31	0.35	1/20 (-26 dB)
	ζ = 0.707				

These data show that errors are minimized if a filter is used having a damping factor of 0.707 and cutoff frequency of around 5.6 Hz for pitch rates of 7 degrees/second. Filtering of that type gave errors in C_D of 0.018 percent of maximum, which was equivalent to less than one-tenth drag count (reducing the filter frequency to 2.2 Hz increased the maximum drag error due to filtering to 1.8 counts). It reduced 60-Hz line frequency noise by a factor of 116 (41 dB) and 300 Hz aerodynamic noise (estimated to be the lowest frequency of aerodynamic noise in HIRT) by a factor of 580 (55 dB).

The filtering is normally applied to the six balance components. It can be argued that the above analysis does not describe the actual filtering in a wind tunnel because it assumes that the aerodynamic coefficients are being filtered. However, the balance components are combined in a six-by-six matrix, then resolved into wind axes and multiplied by scaling constants to produce the coefficients. If all these processes were linear, it would be immaterial (at least from a mathematical standpoint) whether the filtering is applied to the balance components or to the aerodynamic coefficients (by the principle of superposition). While the processes are admittedly not completely linear, it is believed that they approach linearity sufficiently close to make this investigation a good approximation of the actual system.

In summary, this analysis indicates that by using filtering with a damping factor of 0.707, error due to filtering can be held to within acceptable limits for pitch rates of 7 degrees/second. This conclusion does not apply if model sting dynamics at 10 Hz are excessive.

9. "Applications Manual for Operational Amplifiers," Philbrick/Nexus Research, a Teledyne Co., Dedham, Massachusetts.

4.1.4 Data Acquisition

The short run time projected for HIRT imposes some demands on data acquisition capabilities. The data acquisition system must not only collect and store a sufficient amount of data during the short testing time to completely document the run, but must also maintain the correct functional relationship between parameters changing rapidly with time.

The requirement to collect a sufficient amount of data merely requires that all data channels be sampled often enough to show adequate detail for each recorded variable. For force testing, a sweep of all data channels for each increment of one-tenth degree on angle of attack is considered sufficient for this purpose. Based on this requirement, a rate of sweeping all data channels seventy times per second would be adequate for pitch rates of 7 degrees per second.

Most modern high speed data systems use serial data sampling. This results in a finite time between data samples of successive components. The assumption is usually made, however, in data reduction that all components within a single group of components were sampled simultaneously. When data are recorded that are varying rapidly with time, a significant error is introduced by this assumption unless the data sampling rate is very fast. For instance, there may be a significant difference between the actual angle of attack and that at which a data component is recorded. A reasonable requirement would be that the total model motion during the time of data sampling should not exceed the normal uncertainty in angle of attack. A maximum time separation of three milliseconds for all the angle-of-attack related channels would ensure that, at 7 degrees per second, less than 0.02 degree would be added to the uncertainty of angle of attack.

Data acquisition systems are currently available that meet and significantly exceed these timing requirements with system accuracies of ±0.03% of range. It is apparent that data acquisition systems can be obtained that do not add significantly to the data uncertainties expected for HIRT.

4.1.5 Flow Field Lag

Probably the most fundamental concern associated with high pitch rate testing is the adequacy of the flow field response to model pitch rate. While the other high pitch rate problems lend themselves to solution (or at least improvement), it appears that the time response of the pressure field around the model constitutes the ultimate limit on pitch rate for a particular model in a particular flow field.

The time response of disturbances in the aerodynamic flow field can be estimated by theoretical techniques. These estimates can then be translated into estimated errors incurred for different model pitch rates. However, while the gross effects of pitch rate on data accuracy could be estimated, the time response of each model is clearly a function not only of the size and shape of the model, but also of Mach number and other tunnel parameters.

An attempt has been made at the General Dynamics High Speed Wind Tunnel to investigate this problem using experimental techniques. Comparison data have been taken on models over a wide range of pitch rates with the intent of finding the functional relationship between pitch rate and error in aerodynamic coefficients. Assuming that under ideal conditions the effects of all the other sources of error can be eliminated or compensated, any remaining error would be attributable to lag in the flow stabilization about the model as it is pitched.

One phase of the investigation was conducted using a delta wing airplane model. This model was tested over the range of angle of attack from -2 to +9 degrees and over a wide range of pitch rates. The data presented here were taken at M = 1.2 and at a Reynolds number of 4.5×10^6 per foot in the General Dynamics High Speed Wind Tunnel. (A similar investigation was conducted at M = 0.8, which showed virtually identical results.)

Several parameters normally derived from wind tunnel force data were computed from the data taken at each of the pitch rates. These parameters (C_{m_α}, C_{L_α}, α at $C_L = 0$, $C_{D_{min}}$, and C_D at $C_L = 0.2$ and $C_L = 0.3$) were computed for each run using least squares curve fits of the data. The parameters were then analyzed for any correlation with pitch rate. The data from this study are shown in Figure 18.

It is apparent from Figure 18 that there is no significant effect of pitch rate on the data. Out of the three drag parameters, the largest variation between the parameters at 9 degrees per second pitch rate, and pitch and pause conditions, was less than 5 counts. A repeatability check run was made a 3 degrees per second. For the drag parameters, the disagreement between the two runs made at 3 degrees per second was, in each case, greater than the disagreement between the fastest pitch rate and the pitch and pause run.

In a 4 × 4-foot wind tunnel, using average sized models, pitch rates up to nine degrees per second do not significantly affect data uncertainty. While it would be unwise to extrapolate the data taken during this investigation over any significant range of pitch rate, the absence of any trends in the data would tend to indicate that one could pitch somewhat faster without risking any serious error. Therefore, there appears to be no significant problem of flow field lag for the pitch rates projected in the HIRT operation.

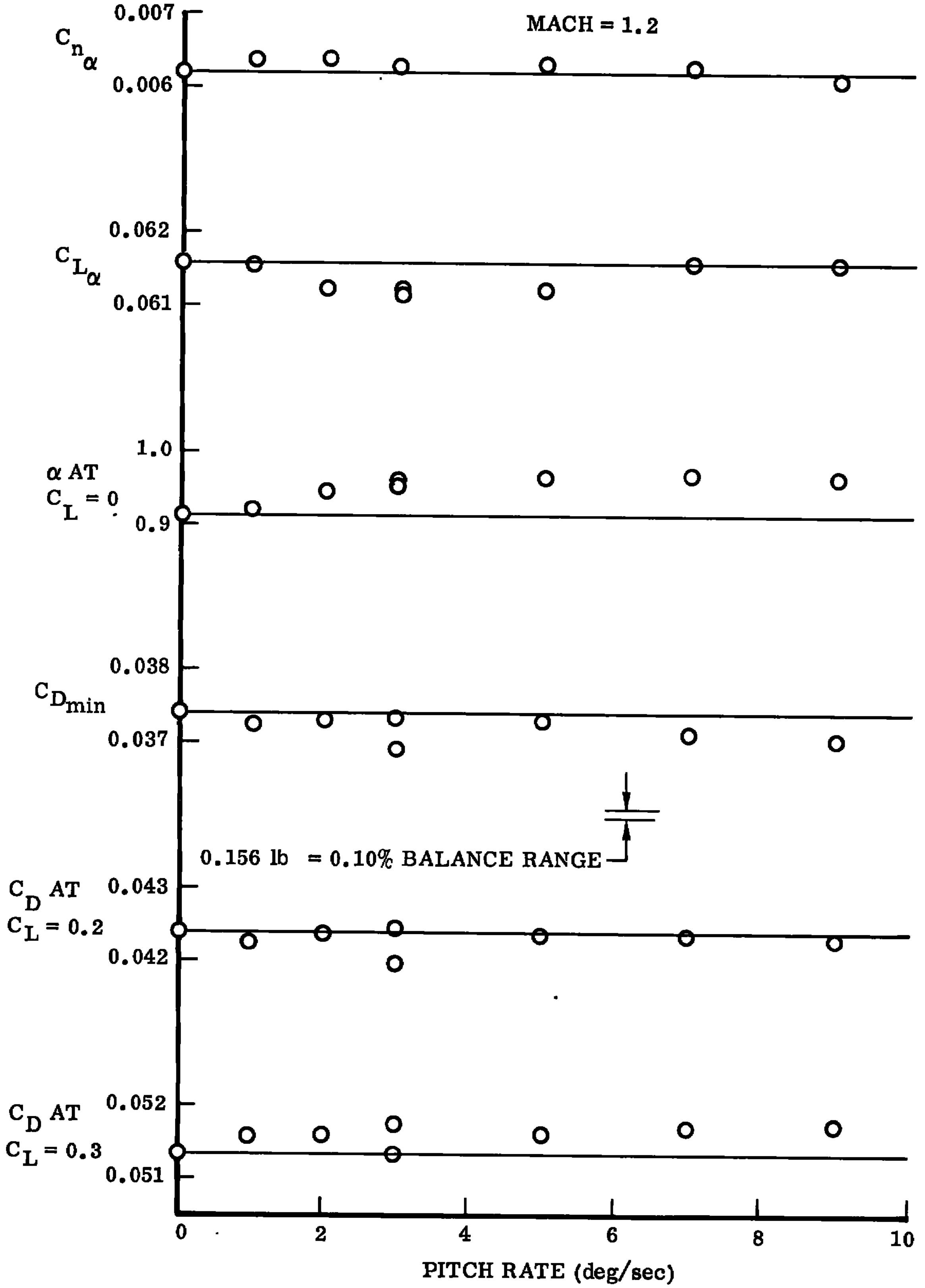


Figure 18. Effect of Pitch Rate on Airplane Model Data

4.2 HIGH DYNAMIC PRESSURE

Another area of testing in which HIRT differs from typical transonic tunnels is in the range of dynamic pressure. In order to attain the flight Reynolds numbers for which HIRT is being designed, it will be necessary to use dynamic pressures of over 200 psi. This is a factor of ten above the typical operating dynamic pressure of current transonic blowdown tunnels.

A representative test plan given in Reference 10 shows test runs to be conducted in HIRT at dynamic pressures from 120 to 17 psi. Thus, the dynamic pressure range may be seven or ten to one. Both the level of the higher dynamic pressure and the overall range of dynamic pressure may be considered to have significance in assessing the uncertainty in test data. These problems will appear in the area of balance design and selection and in aeroelasticity of model components.

4.2.1 Balance Loads

For a given size model, the maximum balance loading in HIRT can be expected to be up to ten times that in most other transonic facilities. Thus, while the balance dimensions are limited by model size to the same general size as those used at lower Reynolds number facilities, the rated loads must be much higher. Such balances designed for HIRT might exhibit significant accuracy penalties.

In order to evaluate the balance design problem for HIRT, a special study has been made, which is reported in Reference 11. The load capacity of balances has been related to the balance load capability factor:

$$C_1 = \frac{L}{D^2}$$

Reference 12 evaluates the capability of currently available balances and determines the general range of capability. This capability is summarized as follows:

	C_1
Present balances	500 lb/in.^{2}
Present balances, maximum capability	890 - 1000 lb/in.^{2}
Projected future capability	1600 - 1780 lb/in.^{2}

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10. R. F. Starr, "HIRT Operational Efficiency and its Impact on Representative Test Programs," AEDC VKF/LR-AD/OC-5, September 1972.
11. M. L. Kuszewski et al, "Study of Six-Component Internal Strain Gage Balances for Use in the HIRT Facility," General Dynamics/Convair Aerospace Division Report CASD-AFS-73-009.
12. "Research Requirements and Ground Facility Synthesis," NASA CR 114325, October 1970.

For a subsonic transport aircraft, with a maximum test lift coefficient of 0.8, the balance load capability factor must be approximately 8 times the maximum dynamic pressure. HIRT operation at dynamic pressures of 200 psi therefore requires balance load factors of 1600 psi. The HIRT balance study evaluated several balances with balance load capabilities in this range and these balances were calibrated to determine accuracy. The results are shown in Table 8. Also included is the accuracy of data on a conventional medium load capability balance. It is evident that the higher load capabilities are achieved at some sacrifice in balance accuracy, particularly drag. The impact on the total drag measurement in coefficient form is also shown in the table. The error in drag coefficient due to balance error is increased from 0.0002 for a conventional balance to 0.0009 for the highly loaded design. It appears that force balance accuracy is one of the major problems facing HIRT in matching the accuracy performance of present wind tunnels.

The balance accuracy problem is compounded for HIRT by the wide range in available operating conditions. One of the greatest hazards to balance accuracy is the use of a balance at a small fraction of its rated load. This practice magnifies the error far beyond the errors noted in Table 8. Therefore, a necessary condition to limit the level of balance error in HIRT will be strict adherence to balance scaling policy. This policy should require that balance selection be made in the light of required data precision as well as matching maximum loads.

Table 8. Effect of Balance Capacity on Accuracy of Drag Measurement

Balance	Load Factor, C_1 (lb/in.^{2})	Normal Force Accuracy Range (%)	Axial Force Accuracy Range (%)	Normal Force Contribution to C_D Error	Axial Force Contribution to C_D Error	Total C_D Error
A	240	0.05	0.11	0.00013	0.00014	0.00019
B	945	0.08	0.24	0.00021	0.00020	0.00028
C	1,440	0.12	0.63	0.00031	0.00086	0.00091

Notes:

1. Balances A and C have same diameter.

2. Data for Balance C from Table 14, Reference 8.

It should be noted that the high load balances analyzed above are prototypes that demonstrate the capability to design and build such balances. The process of refinement is already underway and may result in improved designs. It is conceivable that such development might achieve accuracies comparable to those produced by lower load designs. Since balance accuracy appears to be one of the major accuracy problems for HIRT, there should be continuing work to improve balance accuracy at high balance load factor.

4.2.2 Aeroelasticity

At the higher Reynolds numbers for which HIRT is designed, the models will be subjected to stresses not common in other facilities. These stresses have been treated in other studies being performed at General Dynamics in conjunction with this study, (References 13 and 14).

One of the effects of the abnormal model stress is a significant deformation of the model shape. This change in model geometry creates a change in the measured loads on the model which, in turn, modifies the aerodynamic coefficients. The aeroelastic deformation represents a change in model configuration and results in errors in the aerodynamic data. However, the actual uncertainty in aerodynamic coefficients resulting from aeroelastic effects is a function of the deformation of both model and full-scale airplane. Since the wings of airplanes twist and bend in response to aerodynamic loads in flight, the coefficients are correct only when the wind tunnel model duplicates the shape of the full-scale airplane under the test conditions.

It is possible to pre-twist the wings of the model to duplicate the shape of the airplane at any given set of flight conditions. This agreement in shape holds for only that one condition of loading, except for cases in which both the airplane and model have identical aeroelastic characteristics.

This special case involving similar elastic properties in the model and the airplane has been suggested as a model design goal for use with HIRT. Several flight conditions for two airplanes were analyzed in one of the studies mentioned earlier. For the conditions analyzed, the wing twist of the model tested in HIRT at Reynolds numbers matched to flight agreed well enough with the true airplane twist that the predicted error in drag coefficient was less than 15 counts (0.0015).

It may be possible to reduce the level of error in HIRT drag data by the use of several interchangeable model wings, each with a twist designed to duplicate a given airplane flight condition; or experience may produce sufficient information to allow reliable corrections to be made to the drag data.

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13. W. K. Alexander et al, "Study of Multipiece, Flow-Through Wind Tunnel Models for HIRT," General Dynamics/Convair Aerospace Division Report AEDC-TR-73-47, December 1973.

14. R. L. Holt et al, "Study of Model Aeroelastic Characteristics in the Proposed High Reynolds Number Transonic Wind Tunnel (HIRT) in Reference to the Aeroelastic Nature of the Flight Vehicle," General Dynamics/Convair Aerospace Division Report AEDC-TR-74-62, December 1973.

Regardless of remedies that might be used, the analysis indicates that in each case the combination of the HIRT model and the dynamic pressure characteristics of HIRT would produce better geometric agreement between model and airplane than the nearly rigid models currently used in most transonic wind tunnels. Figure 19 shows the characteristic incremental drag coefficient predicted for three model designs for testing the Advanced Technology Transport (ATT). The locus for each model was obtained for various angles of attack. The models were all assumed to be built with the same pretwist at $\alpha = 6$ degrees. At angles other than 6 degrees, a drag error is produced due to the difference in aeroelastic wing twist of the various models.

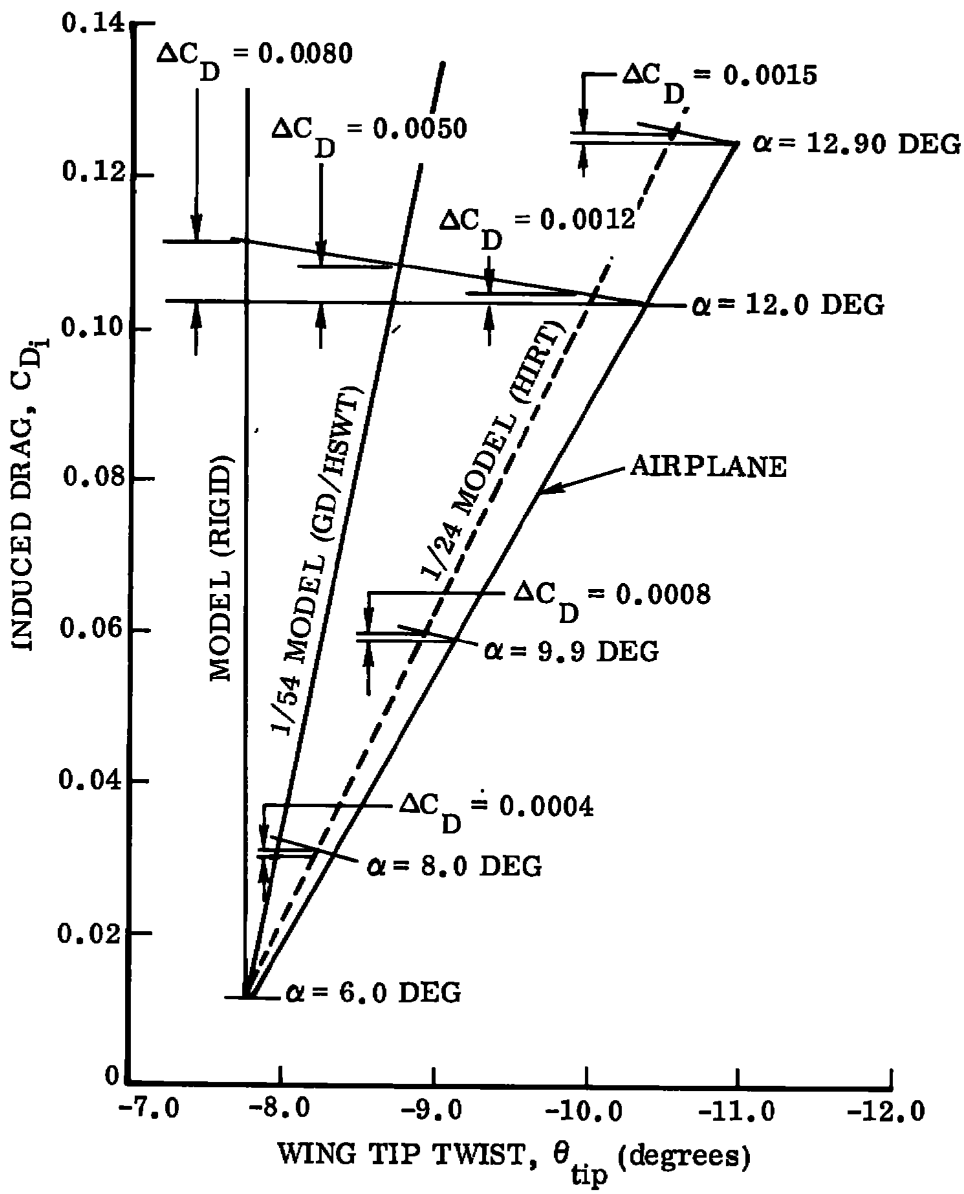

Figure 19. Effect of Wing Tip Twist on Drag

As an example of the relative disagreement in uncorrected drag coefficient for the three models, one can examine the conditions existing at 12 degrees angle of attack. While the HIRT model's aeroelastic divergence from the airplane represents a C_D of only about 12 counts, a similar model scaled down in size (1/54-scale) and run at dynamic pressure typically used in 4-foot blowdown transonic tunnels (1200 psf), would show a difference of roughly 50 counts. A totally rigid model under the same conditions would disagree with the airplane by amounts equivalent to over 80 drag counts.

It is apparent from these considerations that the level of uncertainty to be expected in HIRT data as a result of model elasticity hinges upon three assumptions:

a. The aeroelastic deformation of the airplane being tested can be predicted or measured over the test load range.

b. The aeroelastic deformation of models being tested in HIRT can be measured over the test load range.

c. Models can be built that will deform in a manner similar to the airplane they simulate.

If these conditions are met, indications are that the aeroelastic error incurred in HIRT testing will be no greater than that produced by other wind tunnels. Even in cases where corrections are made based on predictable difference in deformation between airplane and model, the HIRT deforming model would be an advantage since the uncertainty in a small correction is usually less than that in a large one.

4.2.3 Environmental Effects

The operation of the HIRT facility will impose on the model certain environmental effects that are not characteristic of conventional wind tunnels. These effects result from the Ludwieg tube operation, which imposes on the model sudden changes in both temperature and pressure.

In the HIRT facility the starting process involves the acceleration of the air in the charge tube through the expansion wave created by opening the starting valves. This process is accompanied by a drop in temperature of the charge tube air to a stagnation value about 80 percent of the initial air temperature. If the model is at the pre-run temperature, substantial temperature differential will exist between the stagnation temperature of the flow and the model during the run. This problem has been studied in detail by others (Reference 15), and the effect of the resulting heat transfer on data accuracy is documented in those studies. However, a suggested solution to this

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15. J. E. Green, D. J. Weeks, and P. G. Pugh, "Some Observations upon the Influence of Charge-Tube Mach-Number upon the Utility of Flows Generated by Expansion Waves," a preliminary issue.

problem is to pre-cool the model to the expected running temperature so that the proper heat transfer relationship between model and flow is preserved. Such a pre-cooled model may present some problems for balance and transducer operation.

In wind tunnels, temperature effects on instrumentation can be divided into two main categories. The first is the dependence of instrument calibration on the absolute temperature. These effects result from changes in the modulus of materials with temperature and temperature sensitivity of electronic components. Thus a calibration performed at one temperature will not be entirely valid for operation at a different temperature.

The variation of apparent microstrain of several strain gage alloys with temperature is shown in Figures 20 and 21 (from Reference 16). These data show approximately 0.5 percent change in gage factor per 100°F. These two effects combine with other factors to produce a combined change as high as 3.5 percent per 100°F. Figure 22 shows the variation of the modulus of 17-4PH stainless steel with temperature. These data indicate a change in modulus of 2.5 percent per 100°F.

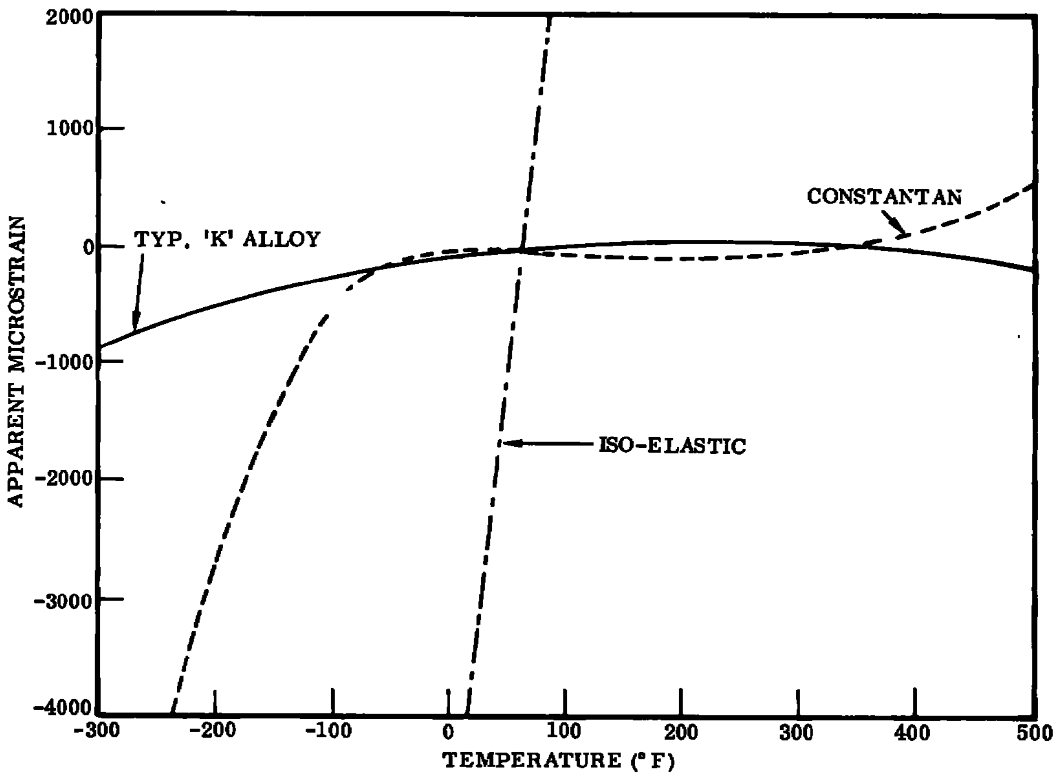

Figure 20. Effect of Temperature on Strain

16. "Apparent Strain and Gage Factor," Micro-Measurements, a Division of Vishey Intertechnology, Inc., TN-128, August 1968.

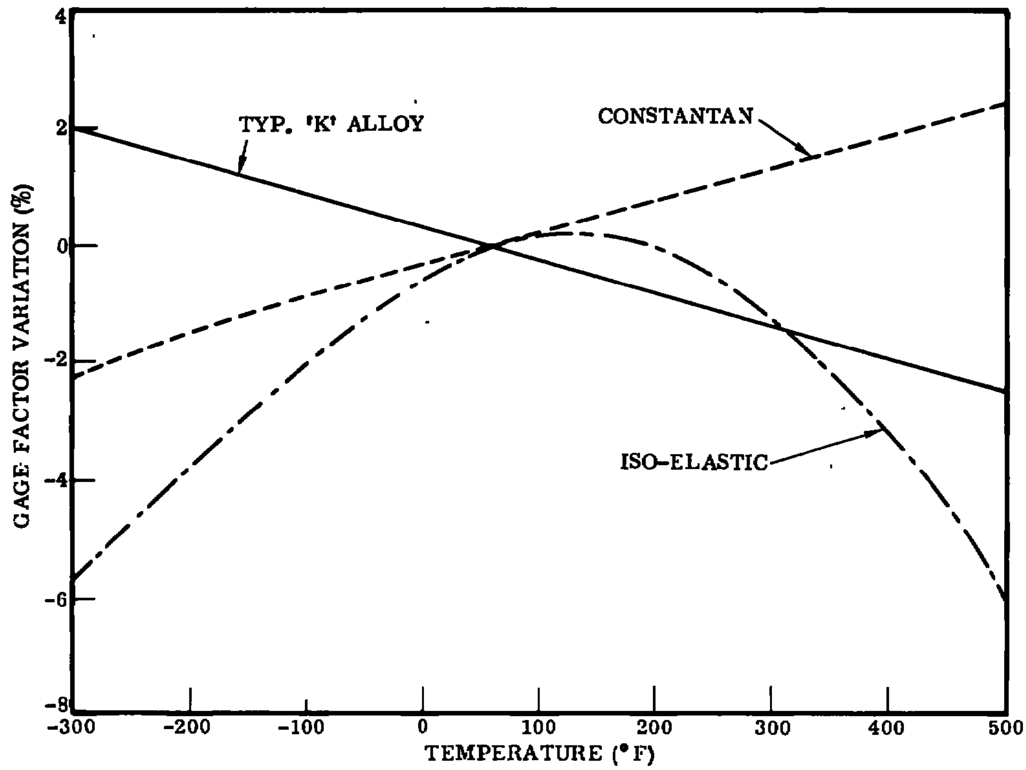

Figure 21. Gage Factor of Micro-Measurements Alloys

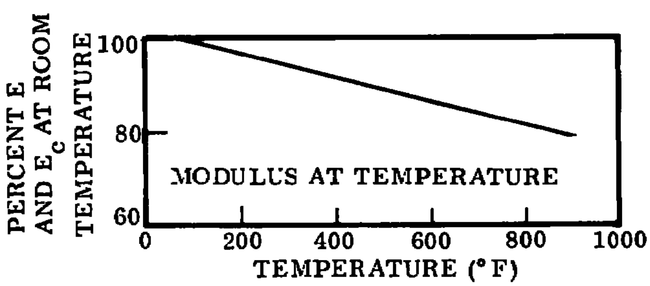

Figure 22. Effect of Temperature on Tensile and Compressive Modulus of 17-4 PH (H 900) Stainless Steels

The second effect is that of zero shift with temperature. This results from changes in temperature occurring between the pre-run zero load point and the actual data recording during the run. Both the calibration and zero shift problem can be significantly reduced by controlling the thermal environment of the balances and transducers. This is a more effective method than relying only on temperature compensation of the instruments themselves. Although temperature compensation is an effective tool in continuous tunnels where the balance or transducer can achieve equilibrium with its environment, it is of questionable value in a short run time facility where thermal equilibrium of the balance is rarely achieved. Therefore, it must be assumed that the thermal environment of the balances and transducers for HIRT operation will receive careful attention. The technology is certainly available to provide such thermal control.

If a controlled thermal environment is provided for balances and transducers, pre-cooling the model to the expected model equilibrium temperature should impose no serious problems. Such pre-soaking will reduce the sudden change in temperature that the balance might experience during a run if the model were not pre-cooled.

The sudden change in pressure is also of consequence in the accuracy of strain gage balances for HIRT. Care must be taken that internal cavities in the balance are properly vented so that trapped air does not cause spurious internal balance loading.

A recent study at General Dynamics Convair has indicated that strain gages can be sensitive to sudden ambient pressure changes. This behavior is illustrated in Figure 23. The balance, when subjected to a sudden ambient pressure change, experiences a zero shift. The shifts occur only on certain gages and may be the result of defects in the gaging process. However, the presence of such pressure sensitivity is not indicated by any of the normal checkout and calibration procedures. Balances to be used in HIRT should be qualified for the facility by simulation of the rapid pressure transient to ensure that they do not have the pressure sensitivity. Gages that display this characteristic should be replaced.

In summary, the environmental effects on instrumentation in HIRT are significant, but can be handled by thermal isolation of balances and transducers and qualification of these instruments under HIRT conditions. If proper care is taken, the instrument performance should be equivalent to that provided by present technology.

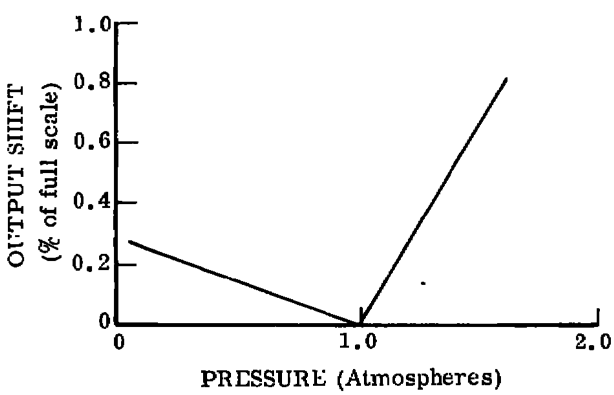

Figure 23. Zero Shift of Gage Output Caused by Sudden Change in Ambient Pressure ($\Delta t < 0.5$ second)

4.3 LUDWIEG TUBE

Other contrasts exist between the Ludwieg tube concept and either conventional blowdown or continuous tunnels that are significant in assessing data uncertainties. These relate to those factors that are specifically Ludwieg tube oriented rather than high Reynolds number oriented.

4.3.1 Flow Quality

The absence of partially open valves or rotating fans in the tunnel circuit upstream of the HIRT test section will preclude sources of noise and flow angularity common in blowdown and continuous wind tunnels. However, while these sources do not exist in the Ludwieg tube design as conceived for HIRT, other sources may be present. Since no Ludwieg tube wind tunnel even approaching the size of HIRT exists at present, it is difficult to predict with certainty the effect of such variables as finite opening time in the start valve and imperfections in the tube walls (Reference 17).

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17. R. F. Starr and C. J. Schueler, "Experimental Studies of a Ludwieg Tube High Reynolds Number Transonic Tunnel," AIAA Paper No. 73-212, January 1973.

4.3.2 Contraction Ratio

The design concept of HIRT excludes the use of a settling chamber upstream of the test section. Instead, the contoured nozzle is connected directly to the charge tube. Since the tube area is approximately twice the nozzle exit area, little reduction in flow irregularities can be expected through the transition section. This design concept has been based on the assumption that the Ludwieg tube produces flow of such a quality that a contraction ratio of two will be adequate. Theory and model tunnel data tend to support this assumption (Reference 17).

At M = 1 conditions the Mach number of the charge tube flow will be about 0.3. Stagnation conditions for the tunnel will be measured in this flow. While the measurement of total pressure and temperature is complicated by the velocity of this flow, instrumentation equipment does exist that can measure these variables within acceptable accuracies.

SECTION V

PREDICTED DATA ACCURACY IN HIRT

A review of the preceding analyses indicates that data accuracy prediction in HIRT falls into three broad categories. First are the areas in which current operational and instrumentation techniques should produce data equivalent to that obtained in present wind tunnels. Second, areas of HIRT operation exist that require special attention but which present no serious problems relating to data accuracy. These areas include surface pressures, environmental effects, and data filtering. The final category includes serious problems involving sting dynamics and balance accuracy. Although not insolvable, these problems require particular attention to provide adequate technology for the HIRT facility. Each of these categories is discussed in this section.

5.1 CURRENT TECHNOLOGY

These areas include:

a. Measurement of flow conditions.

  1. Stagnation pressure.
  2. Stagnation temperature.
  3. Static pressure.
  4. Dynamic pressure.
  5. Mach number.
  6. Reynolds number.
  7. Angle of attack.

b. Base pressure measurement at high pitch rate.

c. Data acquisition.

d. Flow field lag at high pitch rate.

e. Flow quality.

f. Aeroelastic effects.

Of these items, the aeroelastic effects deserve special mention. When the aeroelastic deformation of the actual aircraft is considered, HIRT may produce a more correct simulation than current low Reynolds number facilities. This aspect of wind tunnel testing has received attention in other studies (References 9 and 14). However, it seems clear that HIRT should not be penalized in an area where the consequences of the HIRT operation actually improve the simulation.

5.2 SURFACE PRESSURES, ENVIRONMENTAL EFFECTS, AND DATA FILTERING

The analysis of pressure lag was concerned with measurement of base pressure since this is the primary model pressure measurement involved in force testing. If surface pressures are measured on the model, these pressures may impose a time rate of change that will present lag problems. These problems should be considered for each case to be tested in HIRT. To support such analyses, experimental studies should be performed under the pressure conditions expected in HIRT. Most of the available experimental data in this field are not applicable to HIRT.

The effects of the HIRT test environment may require development of thermal protection and control systems for instrumentation. In any case, balances and other instrumentation to be used in HIRT should be subjected to qualification tests that simulate the HIRT environment.

For pitch rates of up to 7 degrees/second, data filtering to remove high-frequency noise will present no serious problems. However, these filters will not remove noise produced by sting dynamics (discussed below) at 10 Hz. The filter analysis assumed normal continuous aerodynamic data. Any situation that produces data discontinuities (such as flow separation) will present phase problems in the area of the discontinuity.

5.3 STING DYNAMICS AND BALANCE ACCURACY

The operation of HIRT involves a rapid wind tunnel starting process of approximately 0.5 second, followed by a very short run of 2.5 seconds. During the short run, either a full or partial pitch polar will be tested. This process requires that the model be either at its starting point before the run or moved there rapidly after the run begins, then pitched at rates up to 7 degrees/second to record data. If the polar must be divided into segments that are recorded in successive runs, then the model may be at a large angle of attack during the starting process. The motion of the model from its static condition at start to the high pitch rate will involve high angular acceleration.

The rapid loading of the elastic sting-model system by either aerodynamic or inertia loads will result in sting oscillations that will persist throughout the run. This will cause serious data accuracy problems, since the allowable filtering will not remove these oscillatory inputs. Possible solutions to this problem are:

a. Avoid conditions that excite the model-sting system.

   1. Start the tunnel with the model at the zero load condition.

   2. Provide controlled acceleration of the pitch sector.

b. Provide acceleration compensation for balances.

c. Develop highly damped sting designs to reduce damping time.

The restraint of starting the model at the zero load condition imposes an operating limitation on HIRT, since a) additional time is required to move the model to the starting point of the pitch sweep, and b) dividing a sweep between two or more runs is precluded. The acceleration-controlled sector is clearly required, since it provides substantial reduction of the exciting force and the subsequent vibration.

Although acceleration-compensated balances have been used extensively in hypervelocity facilities, their use in HIRT may present particular problems. First, accelerometers in either the balance or model may be difficult to implement for structural reasons. In addition, as noted below, balance accuracy is already a serious problem and imposing the additional requirement of acceleration compensation aggravates this situation.

Assuming that an acceleration-compensated balance could be developed with adequate accuracy, the problem of the oscillatory motion itself and its effect on the aircraft aerodynamics still remains. The motion is quite large (up to 0.25 degree and 0.2 inch) and may violate the assumption of steady flow and attitude conditions. Damped sting designs will alleviate the problem by rapidly damping out the oscillations. These are problems that should be studied in detail.

The second problem requiring attention is the deterioration of balance accuracy as the balance load factor increases beyond normal practice. This situation alone can be expected to double the drag error expected in HIRT, assuming that current prototype high-load balances are representative of those to be used in HIRT. Relatively few of these balances have been built and the technology is new. There is some hope that research and development may improve high-load balances to the point where they are comparable to lower loaded balances. Such development should be undertaken. In addition, careful attention should be given to balance selection so that balances are used close to their design loads.

The expected accuracy of HIRT in the drag measurement is shown below compared with that obtained in current practice. The major source of the added error is the expected accuracy of the drag balance.

Current facilities (correlation studies)	±0.0005
Current facilities (questionnaire)	±0.0005
HIRT projection	±0.0010

The effect of sting dynamics has not been included in this projection, since it is assumed that sting excitation would be avoided. As noted above, such avoidance will impose some operating restrictions.

SECTION VI

CONCLUSIONS

The following conclusions are drawn from the study of wind tunnel data accuracy as it applies to the proposed HIRT facility.

a. Presently operating wind tunnel facilities are marginal in their ability to provide aircraft drag data with sufficient accuracy for performance prediction. This situation is independent of these facilities' inability to simulate conditions at aircraft flight Reynolds numbers.

b. The proposed HIRT facility, while simulating flight Reynolds numbers, may not provide basic data as accurate as existing facilities unless certain outstanding data problems are resolved. However, HIRT's ability to simulate flight Reynolds number and better simulate aeroelastic effects may result in a net improvement in the data despite data accuracy deficiencies.

c. The major problems in HIRT data accuracy are a) the deterioration of balance accuracy at high balance loads and b) the magnitude of model sting dynamics likely to be encountered with HIRT operation. These problems are susceptible to improvement through research and development.

In any test facility, accuracy must be engineered into the design from the start and then maintained by constant attention to data precision by the operating staff. The design and operation of a major national facility such as HIRT presents technical callenges in many areas. Certainly this is true in the area of data precision. There is nothing in the above study which would indicate that the problems of data accuracy in HIRT cannot be resolved with proper attention.